EVALUATION OF PROPERTIES OF ALUMINIUM STRIPS PRODUCED USING A LABORATORY SCALE SINGLE ROLL CONTINUOUS STRIP CASTER

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by

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to the

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INDIAN INSTITUTE OF TECHNOLOGY-KANPUR

May-1994

DEDICATED
TO
MY MOTHER AND WELL-WISHERS

CERTIFICATE

This is to certify that the thesis entitled " *Evaluation of Properties of Aluminium Strips Produced using A Laboratory Scale Single Roll Continuous Strip Caster* " by **Mr. Gummadi Srinivasa Rao** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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CONTENTS

ABSTRACT

Single Roll Strip Casting is a near-net-shape-casting process of producing flat products. The present investigation is a part of an ongoing major project in our laboratory on the design and development of a Single Roll Continuous Strip Caster. This part of investigation is mainly concerned with the evaluation of the properties of Aluminium strips produced under various operating parameters. An investigation has been carried out to examine the effect of various operating parameters such as Speed of rotation of Caster drum, Degree of melt superheat etc. on the cast strip quality and mechanical properties of the strips. And also the effect of hot rolling, cold rolling and annealing on the strip microstructure and mechanical properties has been studied in order to establish the feasibility of this technology for commercial exploitation. Several experiments have been conducted to evaluate the effect of operating parameters on mechanical properties such as strength, ductility and microhardness. Microstructural studies based on Scanning Electron and Optical Microscopy are conducted to examine the grain size and internal quality of the strip cast products.

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CHAPTER 1

INTRODUCTION

The conventional method of producing metallic strips/sheets generally involves casting of large slabs or ingots which are then hot and cold rolled to get the desired product thickness. In the conventional method besides rolling, several other unit operations such as soaking, slab grinding,intermediate annealing, etc. are also required. These operations are quite expensive and require a large amount of energy. As a result, the cost of production is high and productivity is low. An alternative to this conventional route of strips/sheets production is the near-net-shape-casting in which the molten metal is directly transformed into strips/sheets of desired thicknesses. Figure 1.1 enumerates the unit operations involved in producing flat products using conventional and near-net-shape casting routes [1,2]. The general aims of near-net-shape casting [3] are: (1) process shortening thus reducing the cost of production, (2) production of hard-to-roll materials such as high-alloy intermetallic compounds, and (3) creation of new materials such as amorphous metals, high-silicon steels, etc.

For direct strip casting processes the energy required include the energy used for ladle heating, holding, tundish preheating, casting and post casting operations like annealing, rolling, etc. Table 1.1 indicates that about 68% energy saving is possible by near-net-shape-casting instead of Ingot route. Comparison with the conventional continuous casting process indicate that a saving of 61% energy from the use of the latter is possible.

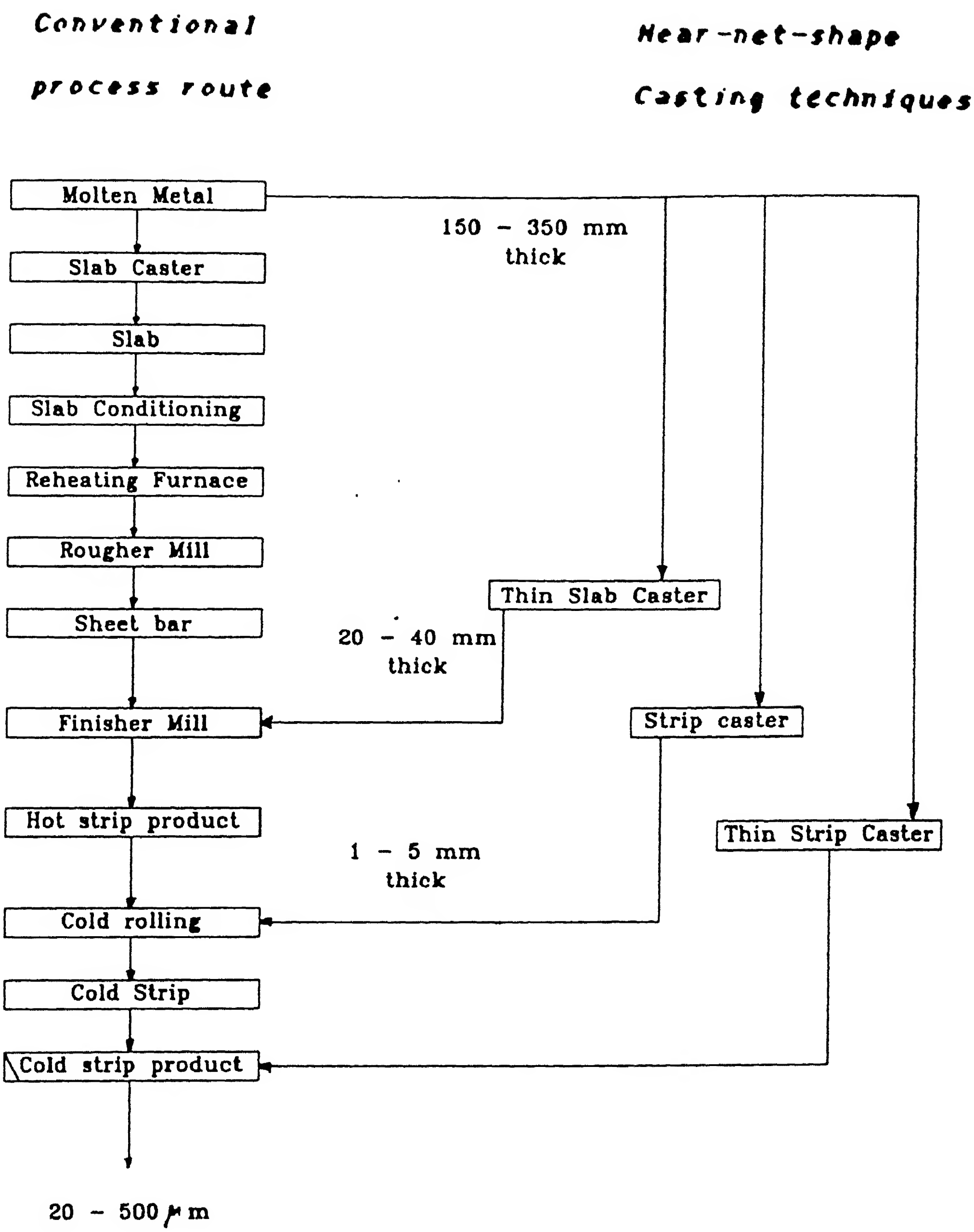


Fig. 1.1 Process routes for producing flat rolled products [1]

Table 1.1 : Comparison of the energy required to make carbon steel strip/sheet by the three processes [3]

Process	kWh /ton Production	kWh/ton Shipped	% Material Loss
Ingot casting	1760	2394	27
Continuous casting (conventional)	1442	1933	25
Direct strip casting	721	750	4

A major negative opinion of the opponents of direct strip casting processes emphasizes the importance of finishing processes [4] such as cold rolling in realizing desirable structure, profile and surface characteristics. According to them the strip cast-materials require little reduction making it difficult to correct problems originating in the casting process and obtain the desired characteristics by downstream rolling. Another negative opinion stresses basic solidification theory, according to which solidification front is composed of non-uniform columnar dendrite structure which does not have high quality.

Mechanical properties of as-cast material should approach that of the conventionally made strips, and there should be no microshrinkages, gas porosity, hot cracks, strip edge curl. There should be uniform microstructure throughout for isotropic mechanical properties.

The benefit of process integration is only achieved when the finishing cost of the strip is reduced (or eliminated). The cost of manufacturing the strip of 0.3 mm thick which includes conventional continuous casting, hot and cold rolling is 85% of the total while the finishing cost (dressing and inspection) is only 15% as shown in Fig. 1.2. It also indicates that energy consumption decreases as As-cast strip thickness decreases. When the surface condition of the strip is same as that of conventional large section cast slab, finishing cost increases rapidly as shown in Fig. 1.3 with decreasing thickness because it is necessary to inspect and condition an increasingly great surface area for the same weight of material and the benefit of process integration disappears quite

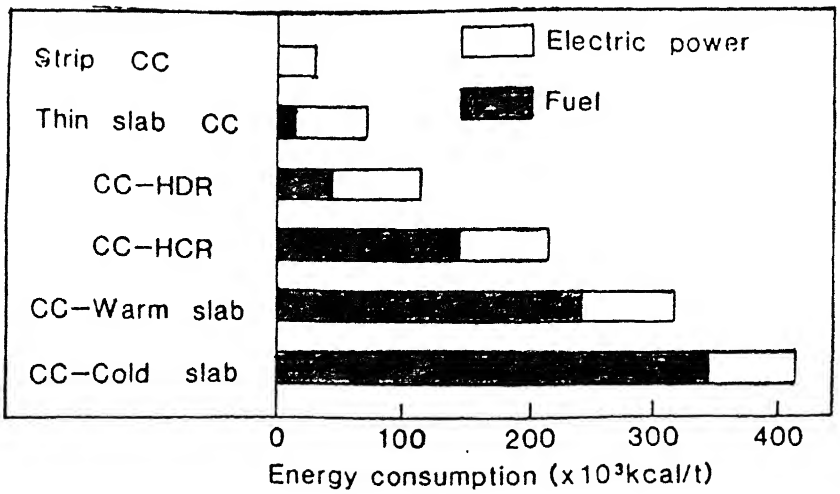


Fig. 1.2 Energy requirement of each technology [4]

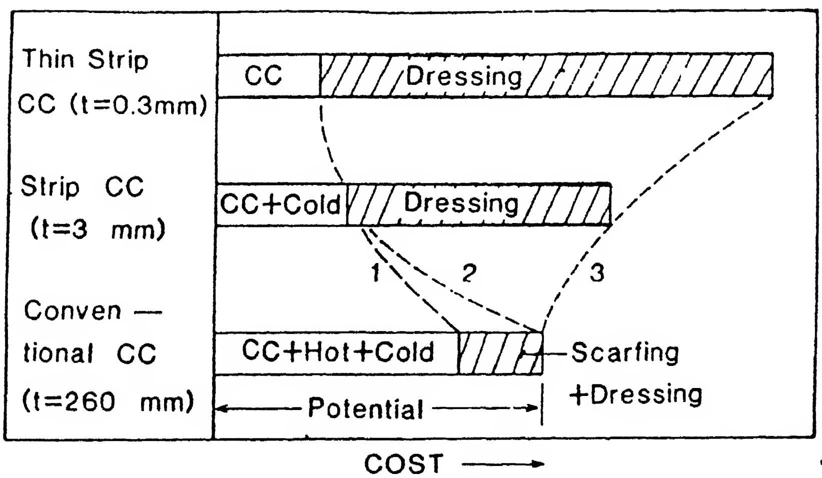


Fig. 1.3 Potential for reducing manufacturing cost [4]

quickly. When the surface condition of As-cast strip is better than that of hot-rolled strip (in conventionally made) then only both the benefit of process integration and decreased finishing costs can be realised.

The direct casting of strips or sheets from molten non-ferrous metal has already been in use on commercial scale for production of aluminum, lead and zinc since 60's. The continuous near-net-shape casting process can be classified into four categories, depending on the thickness of the final product [2].

1. The thick slab caster producing 20-100 mm thick slab which could be directly fed into the finisher mill for hot rolling.
2. The thin slab caster producing 10-20 mm thick which need some limited hot rolling due to the metallurgical reasons.
3. The strip caster producing strip less than 10 mm thickness which may directly go to the cold rolling plant.
4. The thin strip caster which would produce directly a final product equivalent either to as-rolled sheet or to the cold rolled sheet. The thickness of the product here may be fraction of mm.

Several strip casting techniques have been devised for commercial exploitation [2,5-7]. A detailed description of various near-net-shape casting processes has been presented by Bid in his Master's thesis [10]. Because of the importance of rolls in obtaining the desired shape and surface qualities, practical development is centered on only two methods: (i) Single Roll continuous strip caster, and (ii) Twin Roll continuous strip caster. The former of these processes, i.e. the Single Roll continuous strip

caster is the subject of this investigation. A brief description of this caster is given below.

1.1 SINGLE ROLL CONTINUOUS STRIP CASTER [8-10]

Schematic representation of the process is shown in Fig. 1.4. The liquid metal at a particular temperature is held in the tundish in which its level is always kept constant. The tundish has a rectangular nozzle opening at the bottom of the side wall facing the caster drum through which the molten metal continuously flows into the liquid metal pool contained in the annular space between the rotating water cooled drum and the tundish wall. The rotating drum drags along with it a part of metal from liquid metal pool which on solidification forms a skin of solidified metal strip. The skin continuous to grow as long as it is in contact with the molten metal in the pool. A knife edge located on the other side of the caster drum peels off the solidified strip from the drum after it has grown to its full thickness. Heat is continuously extracted from the solidified strip through the caster drum by water spray nozzle located inside the hallow drum. For a given liquid metal head in the tundish strips of different thicknesses can be produced by varying the speed of rotation of the caster drum.

At the point of first contact between the caster drum and the liquid steel, say at angular position β_1 , there is instantaneous solidification,and skin of initial thickness is formed. This skin continuously grows during its sojourn through the liquid pool and attains its final desired thickness at the exit end of the pool at angular position β_2 . The solidified strip remains in contact with the liquid pool over the annular position which in turn, is directly

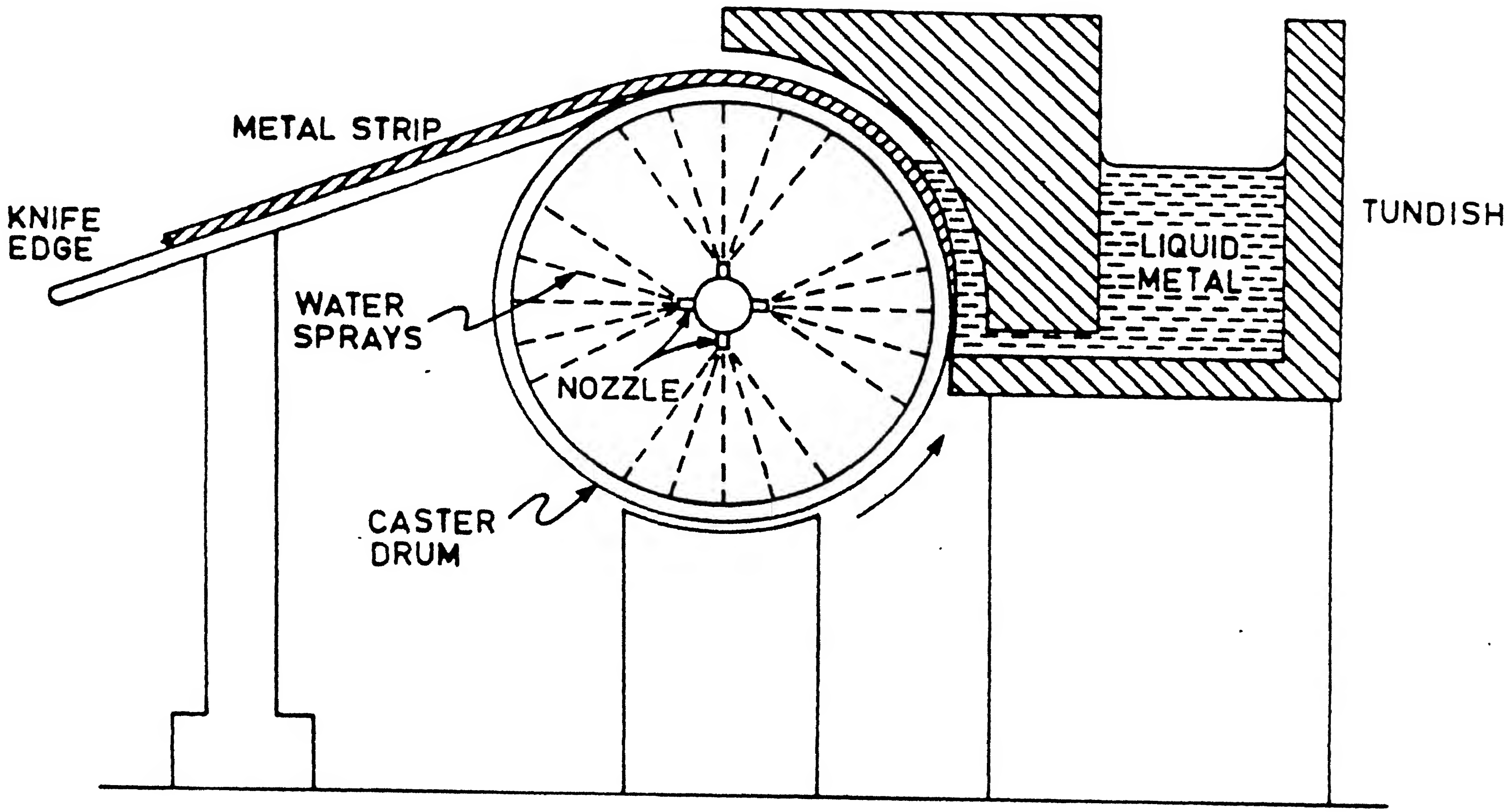


Fig. 1.4 Schematic sketch of the Single Roll (drum) Horizontal Strip Caster [10]

related to the metal head in the tundish.

The entire process can be divided into four distinct zones: (i) liquid steel tundish including the nozzle channel, (ii) liquid steel pool, (iii) solidifying steel strip, and (iv) water cooled caster drum.

The liquid pool is bounded by tundish walls and solidifying steel strips on sides and protruding tundish wall at the bottom. The top-side free surface is open to atmosphere. The molten steel from the pool is being continuously removed in the form of the solidifying strip and this loss of metal in the pool is being replenished continuously by flow of metal from tundish. At steady state the two rates are equal such that the liquid metal level in the pool always remains constant. One surface of the solidifying strip is attached on to the caster drum whereas the other surface is interfaced with molten steel in the liquid pool. It is assumed that the strip is firmly adhered to the caster drum and that there is no slip between the two. The strip is assumed to be moving at the same speed as the caster drum and the residence time of the solidifying strip in the liquid steel pool is directly related to the speed of rotation of the drum which, in turn, determines the final thickness attained by the strip as well as the production rate.

1.2 OBJECTIVE OF THE PRESENT INVESTIGATION

The present investigation is a part of a major project which is currently underway in our laboratory. The project involves developing a comprehensive mathematical model ultimately leading to design criteria for such a caster, validation of mathematical model

using experimental data generated on a laboratory scale single roll strip caster, and finally to examine the feasibility of using such a process for producing steel and non-ferrous metal strips/sheets. The present study partially deals with the latter objective. In the earlier parts of this investigation fabrication of the single roll strip caster initiated by Mehrotra and Coworkers [16-21] production of aluminum strips under various operating parameters which determines the thicknesses have already been completed. This part of the investigation involves the evaluation of mechanical properties and microstructures of the products. This is to see the effect of various operating parameters on the strip quality, and also to see the effect of hot rolling, cold rolling, and annealing on the strip microstructure and mechanical properties so that to establish the feasibility of this technology for commercial exploitation. Many of the strips evaluated in this part of the investigation were those produced in an earlier investigation by Bid [10]. However, if the strips cast under certain specific operation conditions were not available they were produced as a part of this investigation.

CHAPTER 2

PRODUCTION OF ALUMINIUM STRIPS IN SINGLE ROLL CONTINUOUS STRIP CASTER

The design and fabrication of single roll continuous strip caster was initiated by Mehrotra and coworkers [16-21]. The fabrication of the caster was completed, and it was made fully operational in producing aluminum strips at various operating conditions. A brief description of caster design and production method of strips (strip casting) is presented in this chapter.

2.1 SINGLE ROLL STRIP CASTER [10]

A schematic diagram of the caster assembly is shown in Fig. 2.1. The main components of the caster include:

(i) Tundish/Reservoir.

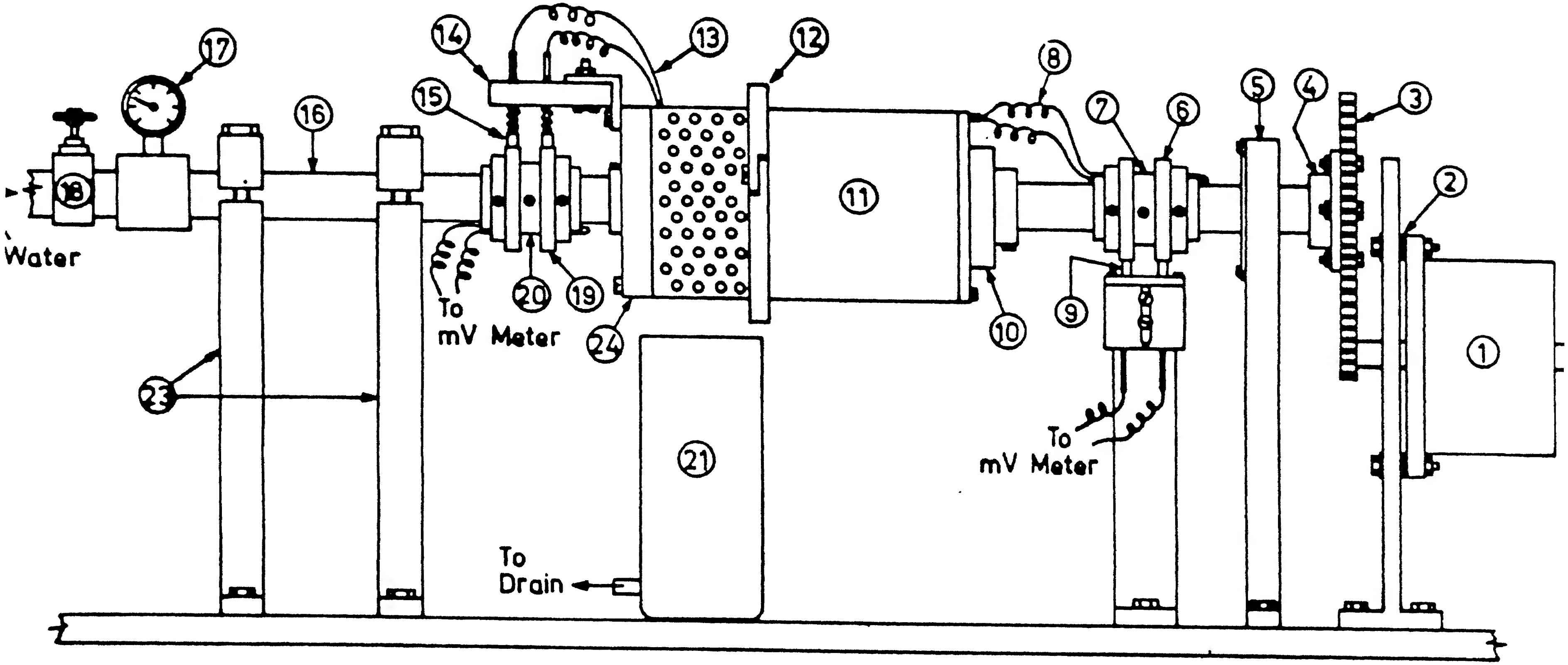
(ii) Caster Drum Assembly.

(iii) Water Spray System to Cool the Caster Drum.

(iv) Knife Edge.

2.1.1 Tundish/Reservoir

Tundish, which is made up of a fireclay brick, primarily acts as a reservoir to hold molten metal, and feeds it on to the rotating caster drum in a controlled manner. The rate of flow of the metal to the drum, which is determined by the rate at which the metal is removed in the form of the solidified strip, is controlled by controlling a constant metal head in the tundish. The tundish wall facing the drum has the same concentric profile as that of the drum. It has a rectangular opening at the bottom of this concentric face that acts as an outlet for the molten metal. The tundish is placed



(1) Stepper Motor (2) Rubber Washer (3) Reduction Gear (4) Brass Coupling (5) Ball Bearing Holder
(6) Copper Ring (Rotating) (7) Teflon Sleeve (Rotating) (8) Thermocouple (9) Carbon Brush
(10) Brass Flange (11) Copper Drum (12) Brass Ring (13) Thermocouple (14) Teflon Plate
(15) Carbon Brush (16) S.S. Tube (17) Pressure Meter (18) Valve (19) Copper Ring (Stationary)
(20) Teflon Sleeve (Stationary) (21) Water Collector Tank (22) Brass Flange (23) M.S. Stand
(24) Cover Plate (Brass).

Fig. 2.1 Schematic diagram of Strip Caster assembly [10]

very close to the caster drum without touching it to avoid scratching of the drum surface. At the same time it is ensured that the gap between the drum surface and the tundish is not large enough to lead to the leakage of the molten metal through this gap. The tundish is placed on a rectangular cast iron platform and is fixed with four hexagonal nuts on each corner.

2.1.2 Caster Drum Assembly : The caster drum is made of high purity (99.9% purity) copper. It is a hollow cylinder with both ends open. The total length is divided into two portions. One is the caster drum portion, while the other is water outlet portion which is drilled with holes on its surface and provides an outlet for the spray water.The inner surface of the drum is tapered towards the water exit as shown in Fig. 2.2, to facilitate the flow of water. Both ends of the drum are fitted with brass flanges. One end of the caster drum is connected to the shaft of the microprocessor controlled stepper motor which can vary its speed between 1.5 to 38 rpm. The other end of the drum is connected to a water pipe line which also holds the water spray assembly inside the drum. The caster drum and the water outlet portion of the drum are separated on the outer surface by a brass ring so that the exit water does not come in contact with the molten metal or the solidifying strip at any time. The caster drum is fitted with thermocouples at two points to measure the temperature continuously during casting. These temperatures are recorded using a P.C based data acquisition system.

2.1.3 Water Spray System to Cool the Caster Drum

Water spray assembly consists of 4 nozzles placed at right angles to each other and in two rows as shown in Fig. 2.2 and Fig.

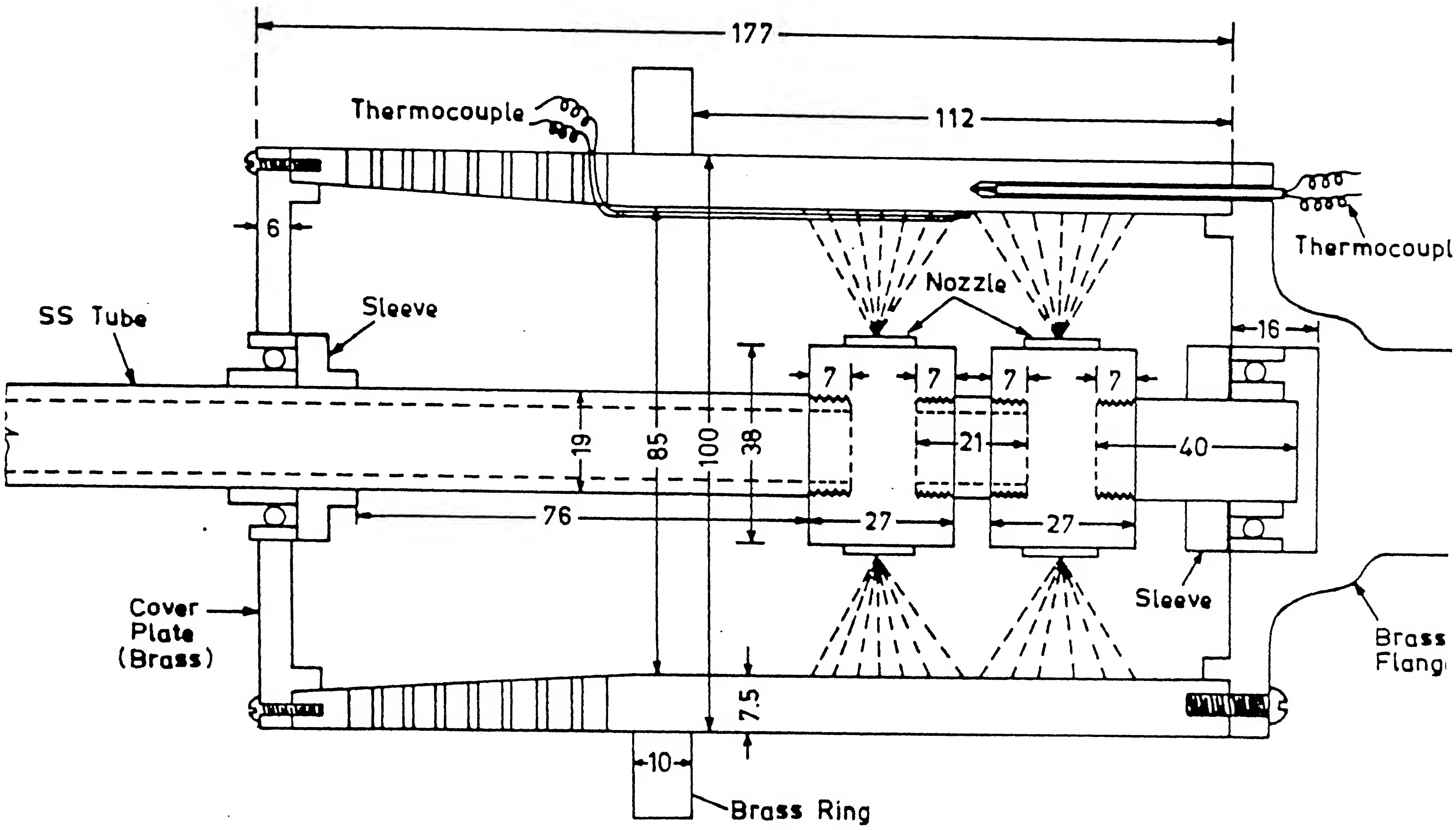


Fig. 2.2 Schematic diagram of Strip Caster drum assembly [10]

1.4. The water spray covers almost the entire surface area of the caster drum to ensure its uniform cooling. The spray nozzles are specially designed such that each nozzle generates a fully developed water cone with cone angle of about 70 degree. The nozzles are fitted through the manifolds on the horizontal stainless steel pipe which passes through the brass flange on one of the open ends of the caster drum. This pipe remains stationary even when the drum is rotating.

2.1.4 Knife Edge

The knife edge, made of aluminium sheet, is fixed on to the platform on which the cast strip moves after solidification (see Fig. 1.4). The platform is on the other side of the caster drum. The main function of the knife edge is to peel off the solidified strip from the caster drum. The position of the knife edge on the drum can be adjusted through its mount by giving it required horizontal and vertical movements.

2.2 STRIP CASTING [10]

2.2.1 Preparation of Melt

About 1.25 kg aluminium is melted in a muffled furnace using graphite crucible/ladle to about 800°C. The charge mainly consists of aluminium ingot (procured from local market), scrap and returns from previous heats. When the charge is fully molten, 10 gm of degasser (hexachloro ethane) and 5 gm of a flux (aluminium chloride) are added to the liquid metal and is stirred with iron rod. After about 15 minutes of this operation the crucible is taken out of the furnace and the impurities (dross) which float at the surface of the

melt are removed with the help of a spoon. The temperature of the melt is continuously monitored during this whole operation using a thermocouple. When the temperature of the melt reaches desired superheat, it is ready for pouring.

2.2.2 Casting of Strips

Before pouring of the metal into the tundish, it is ensured that the tundish is preheated so as to minimize thermal shocks. The stepper motor is started with the help of the microprocessor. The waterline is switched on and a prespecified water flow rate is set. Now the crucible, holding the molten metal, is manually lifted and the metal is poured into the tundish. The pouring is done in such a way that the metal level in the tundish reaches the marked level quickly enough and then it remains more or less constant during the entire casting process. When the metal is poured a molten metal pool is formed in the annular space between the rotating caster drum and the tundish wall. As soon as the drum comes in contact with the molten metal formation of solid strip begins at the drum surface. This strip is gently withdrawn from the pool and brought over the drum surface with the help of dummy bar which in this case is nothing but a bent aluminium piece of the same width as that of the strip. Once the strip comes to the top of the drum it travels on its own. It is separated from the drum by knife edge which also guides it on to the slanted platform in continuous length.

The casting process is continued as long as the molten metal is poured from the crucible, or as long as the strip length does not exceed the platform length. Temperature of the caster drum at two points is continuously monitored and recorded through the PC based

data acquisition system. After the casting is completed, the strips are allowed to cool in air. The operating parameters, which are influencing the strip thickness, such as speed of rotation the caster drum, degree of superheat of the melt, height of the liquid metal in the tundish, tundish nozzle gap, water flow rate are carefully noted and marked on the strip. The length of the strip, width, and average thickness is measured. The surface quality of the strips, such as surface finish and nature of cracks, is examined. The length of the strips in most of the cases is about 1m and the width is about 0.1m. The thickness is varying depending upon the operating conditions and they are discussed in the following sub section.

2.2.3 Strip Thickness

The effect of various operational parameters on strip thicknesses is briefly discussed below.

(i) Speed of rotation of the caster drum is the most critical operating parameter. There is an inverse relationship between speed and the strip thickness. The effect of speed is more predominant at lower speeds.

(ii) Increase in superheat of the liquid metal results in thinner strips.

(iii) Increase in height of the liquid metal in the tundish (metal-head) results in thicker strips.

(iv) Tundish opening size (nozzle-gap) has only a marginal effect on strip thickness. It slightly decreases with increasing nozzle gap.

(v) Cooling water flow rate also has only a marginal effect. The

sheet thickness is slightly increasing with increasing water flow rate. A minimum cooling rate is required to ensure that the caster drum temperature at no stage exceeds its softening temperature.

(vi) Increased stand off distance results in thicker strips.

CHAPTER 3

EXPERIMENTAL PROCEDURE FOR MECHANICAL PROPERTIES MEASUREMENTS AND MICROSTRUCTURE EVALUATION

The main feature of this investigation has been the microstructure and mechanical properties evaluation of the strips produced using the Single Roll continuous strip caster. Table 3.1 lists the various operating conditions under which the strips are cast. These strips are used in this present study. The mechanical properties examined include: (i) tensile strength, (ii) ductility, and (iii) microhardness. The microstructure evaluation has been based on both the scanning electron microscopy and optical microscopy. These measurements have been made on strips subjected to the following conditions:

(i) As-cast
(ii) Hot rolling
(iii) Cold rolling
(iv) Annealing

3.1 PREPARATORY STEPS

3.1.1 Sample Preparation

Samples are cut from the strips both in the longitudinal as well as the transverse directions. It is ensured that these samples are flat, and without any protrusions and cracks on the surface. If scales and protrusions are present on the strip the former is scraped with a wire brush while the latter is removed by filing with a flat file. For specimens in the longitudinal direction, small pieces of 100 x 15 mm are taken in the longitudinal direction of the strip while for the transverse specimens the pieces of 70 x 50 mm are taken in a direction perpendicular to the length of the strip.

TABLE 3.1 Process variables and their ranges used in production of strips [10]

S.No.	Variables	Ranges
1	Speed of rotation of caster drum	1.5 - 38 rpm
2	Degree of superheat of liquid melt	30 - 90°C
3	Height of the liquid metal in the tundish	10 - 40 mm
4	Tundish nozzle gap	10 - 20 mm
5	Water flowrate	0.4 - 0.8 gpm
6	Stand off distance	10 - 20 mm

As the shearing of strip may result in change in mechanical properties of the strip, the samples are cut with a hack-saw.

3.1.2 As-cast Specimens

At least 2 specimens in the longitudinal direction of the strip and 2 in the transverse direction are cut from each strip that is to be tested. These specimens do not require any additional preparation other than the removal of the scales and protrusions.

3.1.3 Hot Rolling

At least 4 samples each are cut in the longitudinal and transverse directions from each strip. These samples are then heated to 500°C in a resistance furnace, for about 15 minutes. These heated samples are then taken out of the furnace for hot rolling on a Two-high rolling mill. Rolling direction is kept parallel to the longitudinal direction of the strip, from which these samples are taken out, for both the longitudinal and transverse samples. The four samples are subjected to 20, 30, 40, and 50 percent deformations, respectively. These deformations are obtained in two passes. During first pass a deformation of 5 percent is given and in the next pass the remaining deformation is obtained for all the samples. This is to avoid cracking, since the as-cast material is prone to cracking, because of the porosity, at higher deformations. The time lag between the two passes is kept to a minimum to avoid heat losses from the samples, thus, ensuring that the rolling temperature is maintained above the recrystallization temperature, that is above 350°C. The samples are allowed to cool in the ambient conditions. These are then taken for making tensile specimens.

3.1.4 Cold Rolling

Cold rolling is carried out for both longitudinal and transverse samples. At least 16 samples are taken in each direction. These are grouped into four batches, each batch consisting of four specimens. These batch of specimens are then cold rolled to 10, 20, 30 and 40 percent deformation, respectively. One cold rolled specimen from each batch is examined under as-rolled condition while the remaining three are subjected to different annealing conditions described in the following sub section. For cold rolling the desired deformation is obtained in successive passes. During each pass only 5 percent deformation is given. This is to avoid cracking of the samples since cast structure is more prone to cracking. The rolling direction is kept the same for both type of samples as is done in the case of hot rolling. During the cold rolling of transverse samples cracks are noticed on the surface in some samples.

3.1.5 Annealing

The cold rolled samples are subjected to annealing at recrystallization temperature depending upon the percentage cold deformation as given in the Table 3.2 for 1, 2, and 3 hours. Annealing is carried out in a resistance furnace. These annealed samples are used for making tensile specimens.

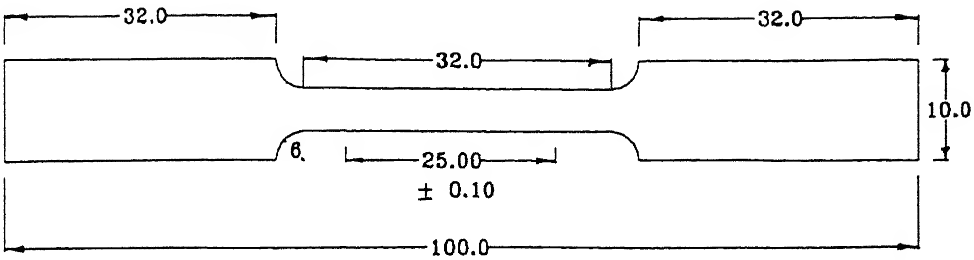
3.2 MECHANICAL PROPERTIES MEASUREMENT

3.2.1 Tensile Strength

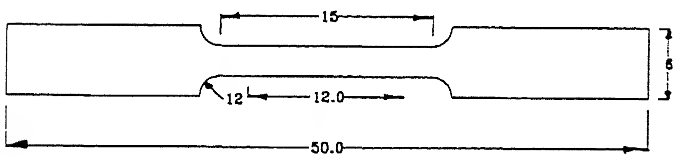
The longitudinal specimens are prepared as per the ASTM standard, while the transverse specimens are prepared as per British Standard specifications, as shown in Figs 3.1(a) and 3.1(b). The

Table 3.2 Recrystallization temperature for Aluminium [11]

Cold work in % deformation	Temperature for complete Recrystallization, ^{o} C
10	460
20	400
30	380
40	360
80	320
98	300



(a) ASTM standard tensile test specimen



(b) British standard tensile test specimen

Fig. 3.1 Tensile test specimens

reason for adopting British Standard in the latter case is because of non-availability of sufficient length in the transverse direction as per ASTM specifications.

Tensile testing for both the longitudinal and transverse directions are carried out on INSTRON 1195 tensile testing machine. These tests are carried out at a cross head displacement of 0.2 mm /min. Automated load versus displacement plots are recorded. From the knowledge of gauge length and area of cross section ultimate tensile strength, 0.2 % Yield strength, and elongation are obtained. The broken specimens are carefully preserved for microstructure and microhardness measurements.

3.2.2 Microhardness Measurement

The samples after optical microscopy [discussed in section 3.3.2] are directly taken for microhardness measurements using 50p load on Vickers scale of LEITZ microhardness tester. The microhardness measurements are made for both the roll-side surface and the top-side surface of the strip across the strip thickness. At least 10 readings are taken on each side and mean of these values is reported as the microhardness of that particular side.

3.3 MICROSCOPY

3.3.1 Scanning Electron Microscopy

3.3.1.1 Preparation of specimens For Scanning Electron Microscopy: The samples for this study are cut with a hacksaw from some of the broken tensile specimens. The broken side edges are examined. The samples are fixed using cold setting compound. For as-cast samples

roll-side surface and top-side surface are carefully noted. These samples are initially ground by a bench grinder followed by a belt grinder.These are then polished using emery papers of grades 0, 1, 2, 3, and 4 till the mirror finish on the surface is obtained. Final stage of polishing is done on a velvet cloth fixed onto a rotating disc using alumina suspension as a lubricant. Initially 1 micron suspension is used. After this the cloth is changed and further polishing is carried out using 0.3 micron alumina suspension. The polishing is continued till a fine mirror surface is obtained. The surface is etched with 10% NaCl for 2 minutes and with 2% HF for 5 sec. These etched specimens are taken for scanning electron microscopy.

3.3.1.2 Scanning Electron Microscopy : The SEM studies are carried out on JEOL JSM 840 A scanning electron microscope. The main attention is focussed on pore size and their distribution, and second phase particles. Photographs are taken at the regions where porosity is higher. It is noticed that some second phase rod shaped particles are present in the matrix. The compositional analysis is carried out at various points on these particles. The composition analysis indicates that these particles basically consists of iron aluminide with other elements such as zinc, copper, manganese, and silicon in small percentages. The presence of these elements in the strip cast material may be due to the impurities that are originating from the main raw material used for making of these strips. The magnification used in this study ranges from 1500 to 4000 depending upon the size of pores and second phase particles. The scanning micrographs presented and discussed in detail in the chapter 4.

3.3.2 Optical Microscopy

3.3.2.1 Preparation of Specimens : The samples after SEM studies are re-grinded and polished as described in section 3.3.1.1. These samples are etched with fresh Keller's etchant for about 15 sec.

3.3.2.2 Optical Microscopic Study : The freshly etched specimens are examined for microstructures under optical microscope. Micrographs are obtained at the magnification of 100. These optical micrographs are reported and discussed in the following chapter.

CHAPTER 4

RESULTS AND DISCUSSION

Using the experimental procedure described in the previous chapter, several experiments (about 90) were carried out to examine the effect of operational parameters, such as speed of rotation of the caster drum, melt superheat, etc. on mechanical properties of the strips. The operating parameters and their ranges used are given in Table 3.1. While some of the strips tested in this investigation were taken from the experimental study by Bid [10], the others were cast as a part of this investigation. To check the reproducibility of our results, several experiments were repeated under identical conditions. The reproducibility of results has been satisfactory in almost all cases. The variation was within ±10%, which considering the nature of the experiments is acceptable. The experimental data points shown in various figures in this chapter represent the mean value if the experiments have been repeated.

4.1 AS-CAST STRIPS

4.1.1 Surface Quality

It is observed that the roll-side surface of the strips is smooth while the top-side surface is somewhat rough. The degree of roughness is more dominant at lower drum rotational speeds as compared to that at higher speeds. Transverse cracks are dominant at higher strip thicknesses. The surface is relatively smoother if the strip is cast from a melt having higher superheat. From the microstructure point of view, however, lower degree of superheat is preferable because it produces equiaxed structure. But, when the

melt superheat is too low there is a danger of nozzle getting chocked which disrupts the whole casting process.

The reason for increase in surface roughness at lower rotational speeds and lower melt superheat may be attributed to larger strip thickness in both the cases. Thicker strip section offers more resistance to heat transfer resulting in reduced solidification rate. This adversely affects the surface quality. Strips of larger thickness are also more prone to transverse cracking due to larger bending stresses that are developed during straightening and peeling off the solidified strip from the drum.

4.1.2 Longitudinal Tensile Strength and Ductility

4.1.2.1 Effect of Speed of Rotation of the Caster Drum : Speed of rotation of the drum not only controls the rate of production of strips, it is also perhaps the most critical parameter influencing the strip thickness and its mechanical properties. Figure 4.1 shows the effect of rotational speed on tensile strength of strips produced at a super heat of 30°C and water flow rate of 0.4 gpm. It is seen that the ultimate tensile strength decreased from 137 to 66.8 MPa when rotational speed was changed from 26 to 4.5 rpm. The effect of speed of rotation on ductility of these strips is shown in Fig. 4.2. Ductility increased from 2.5 to 5.6 percent for variation of rotational speed from 26 to 4.5 rpm.

The reason for increase in strength at higher rotational speeds can be attributed to the increased rate of solidification which, in turn, affects the grain size. The thermal gradient between the drum surface and the liquid metal establishes the requisite heat flow

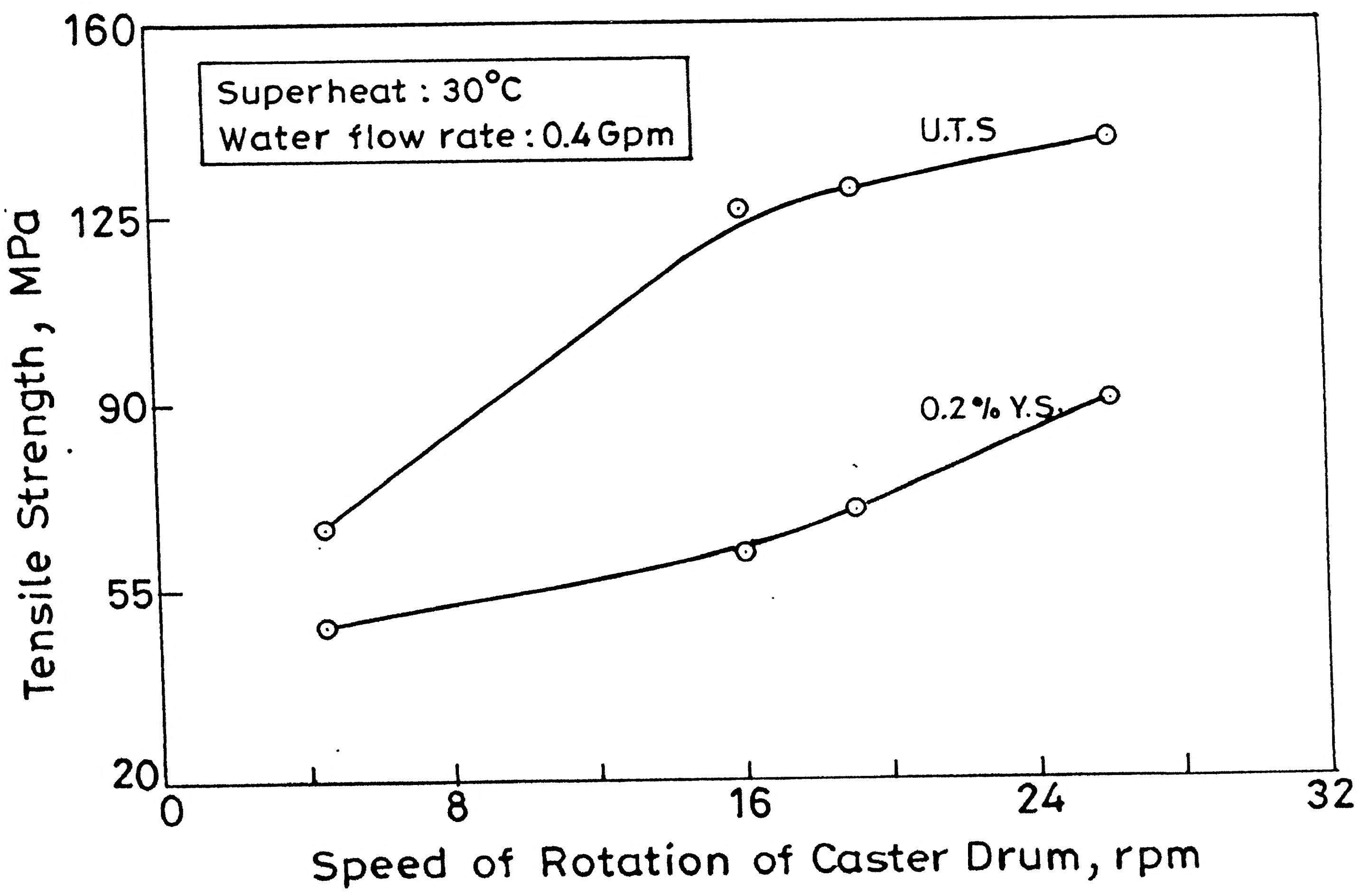


Fig. 4.1 Effect of speed of rotation on As-cast longitudinal strength

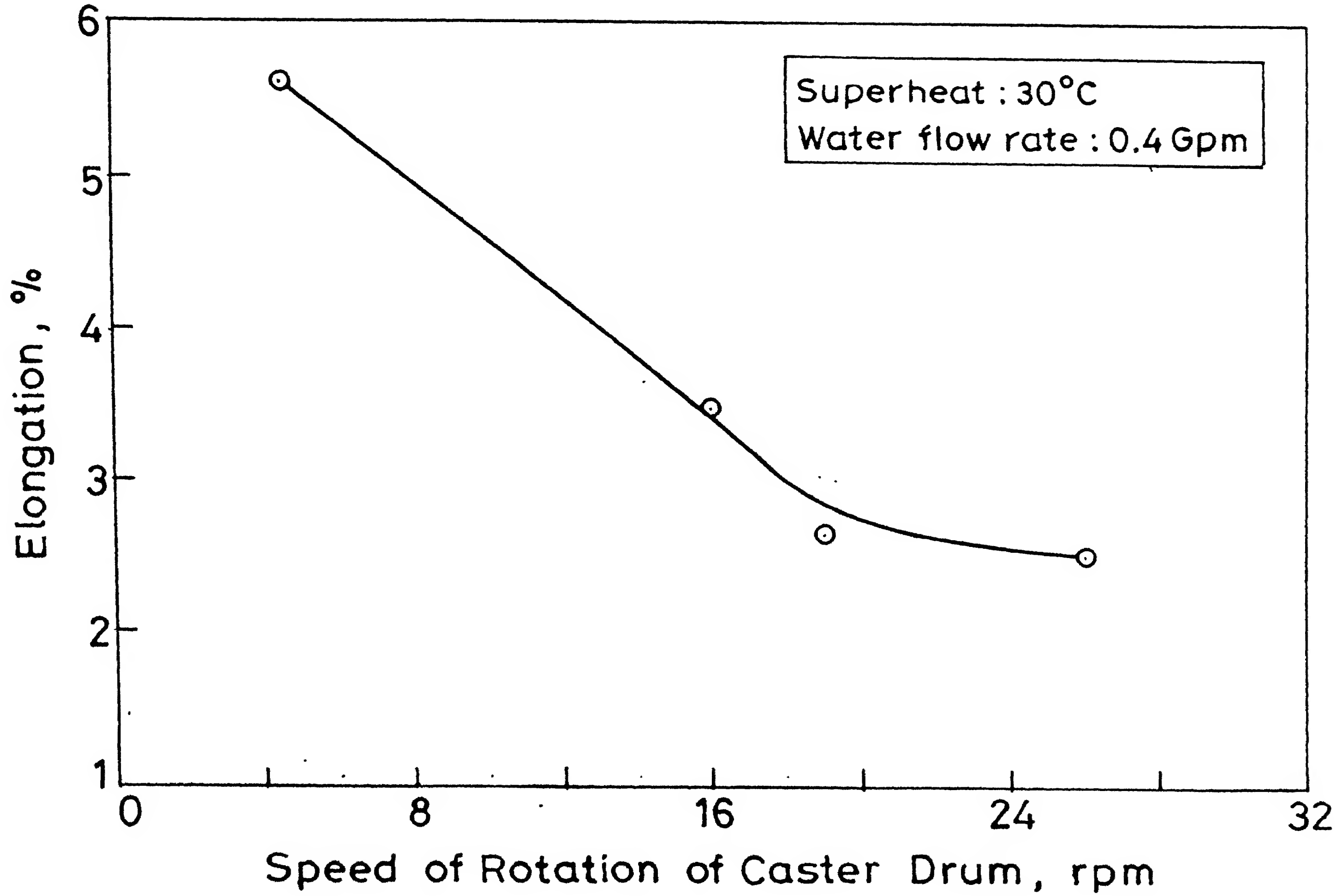


Fig. 4.2 Effect of speed of rotation on as-cast ductility in longitudinal direction

during solidification. This gradient is a function of melt temperature (superheat), the drum surface temperature, and the heat transfer coefficient across the metal/ drum interface. For a rotating drum the contact area increases linearly with increase in rotational speed of the caster drum [12] which directly affects the rate of heat withdrawl from the molten metal pool. It is to be noted that the rotation of the caster drum has two effects :

(i) It increases the heat transfer coefficient at the metal/strip interface because of enhanced fluid flow in the metal pool, and

(ii) New surface is formed continuously between the caster drum and the solidifying strip.

Both the increased mechanical contact between the drum and the strip and the enhanced heat transfer coefficient because of the higher rate of heat withdrawl a product with fine grain structure is produced at higher rotational speeds. The reason for reduction in ductility with increase in speed is partly due to the increased porosity of the strips (discussed later in section 4.1.4) and partly due to the smaller grain size factor.

4.1.2.2 Effect of Melt Superheat : Figs. 4.3 and 4.4 show the effect of melt superheat on strength and ductility of the strips. The strips produced at 30, 60 and 90^{o}C superheat, at a constant drum rotational speed of 16 rpm and water flow rate of 0.4 gpm are considered in these figures. It may be noted that the ultimate tensile strength decreased from 126 MPa to 94 MPa, with an increase in superheat from 30 to 90^{o}C. The variation in ductility, however, exhibited an optimum around 60^{o}C superheat. The ductility increased

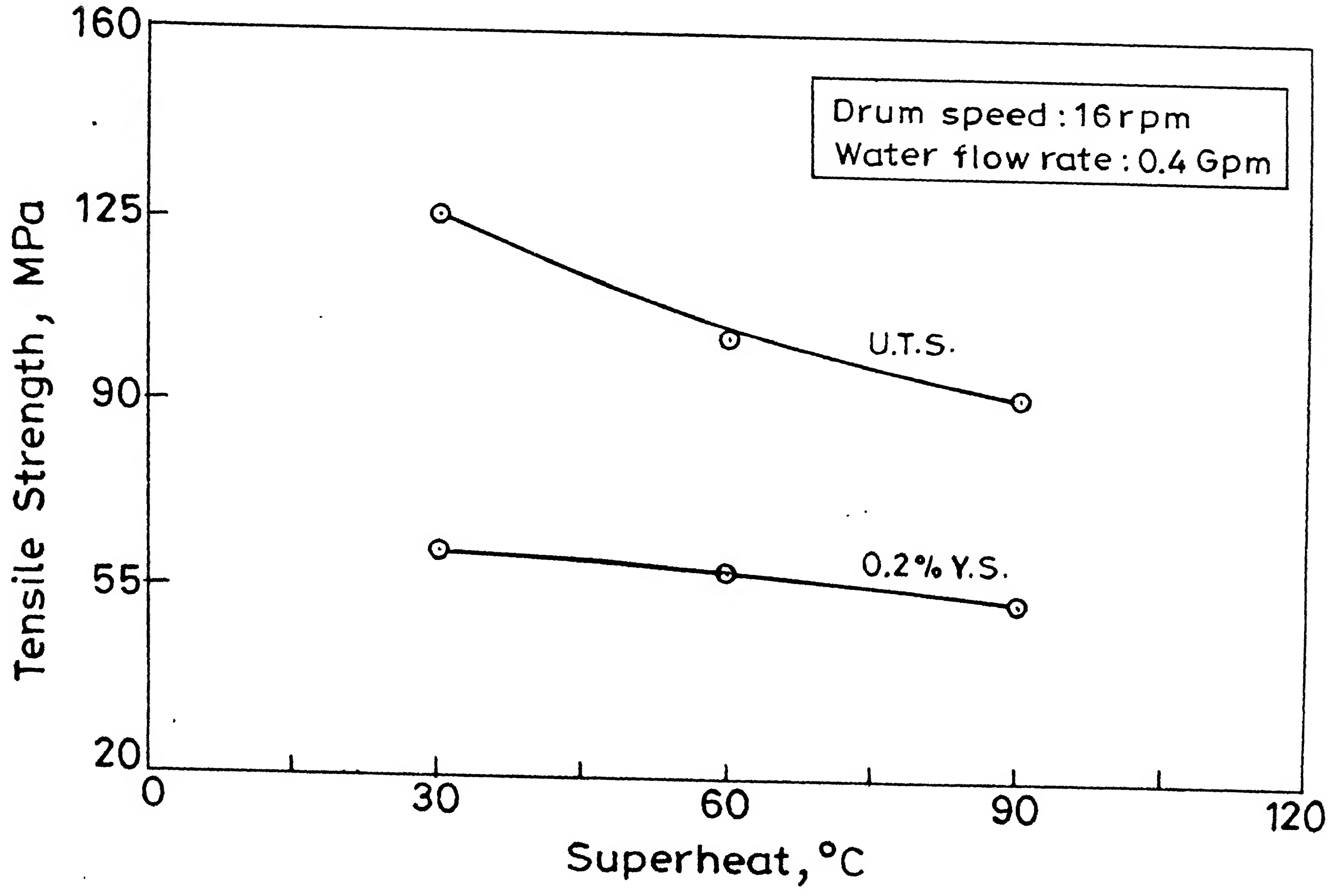


Fig. 4.3 Effect of melt superheat on As-cast longitudinal strength

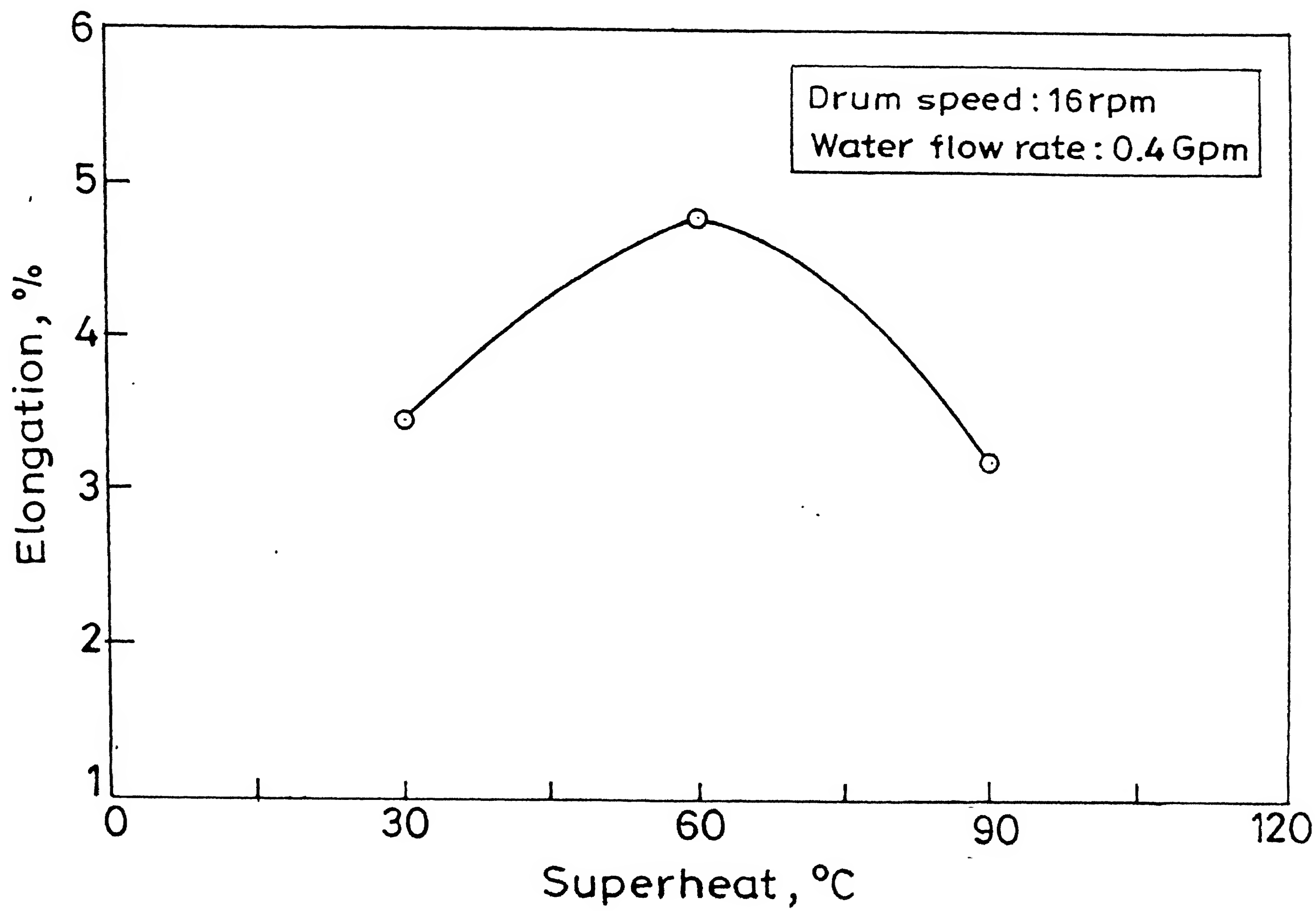


Fig. 4.4 Effect of melt superheat on As-cast ductility in longitudinal direction

from 3.4 to 4.8 percent for an increase in superheat from 30 to 60^{o}C, but it decreased to about 3.2 percent when the superheat was increased further to 90^{o}C.

The reduction in strength and initial increase in ductility is attributed directly to an increase in grain size at higher melt superheats. The decrease in ductility from 4.8 to 3.2 percent on increasing superheat from 60 to 90^{o}C is perhaps due to the dominance of increased porosity over increase in grain size.

4.1.3 Transverse Tensile Strength and Ductility

4.1.3.1 Effect of Speed of Rotation of the Caster Drum : The effect of rotational speed on strength and ductility is similar to that of longitudinal direction as can be seen in Figs 4.5 and 4.6. When the speed was increased from 4.5 rpm to 26 rpm, the ultimate tensile strength increased from 90 MPa to 172 MPa, while the elongation dropped from 5.7 to 2.4 percent.

4.1.3.2 Effect of Melt Superheat : The effect of superheat on strength and ductility are shown in Figs 4.7 and 4.8. In this case also the effect was very similar to that observed in the case of longitudinal tensile strength and ductility.

4.1.4 Internal Porosity

The porosity in the strips may occur primarily due to the following two reasons : (i) shrinkage cavities caused by the reduction in volume of 6 to 7 percent, during transformation [11] from liquid to solid (ii) formation of gas bubbles, due to the release of the dissolved gases in molten aluminium during casting.

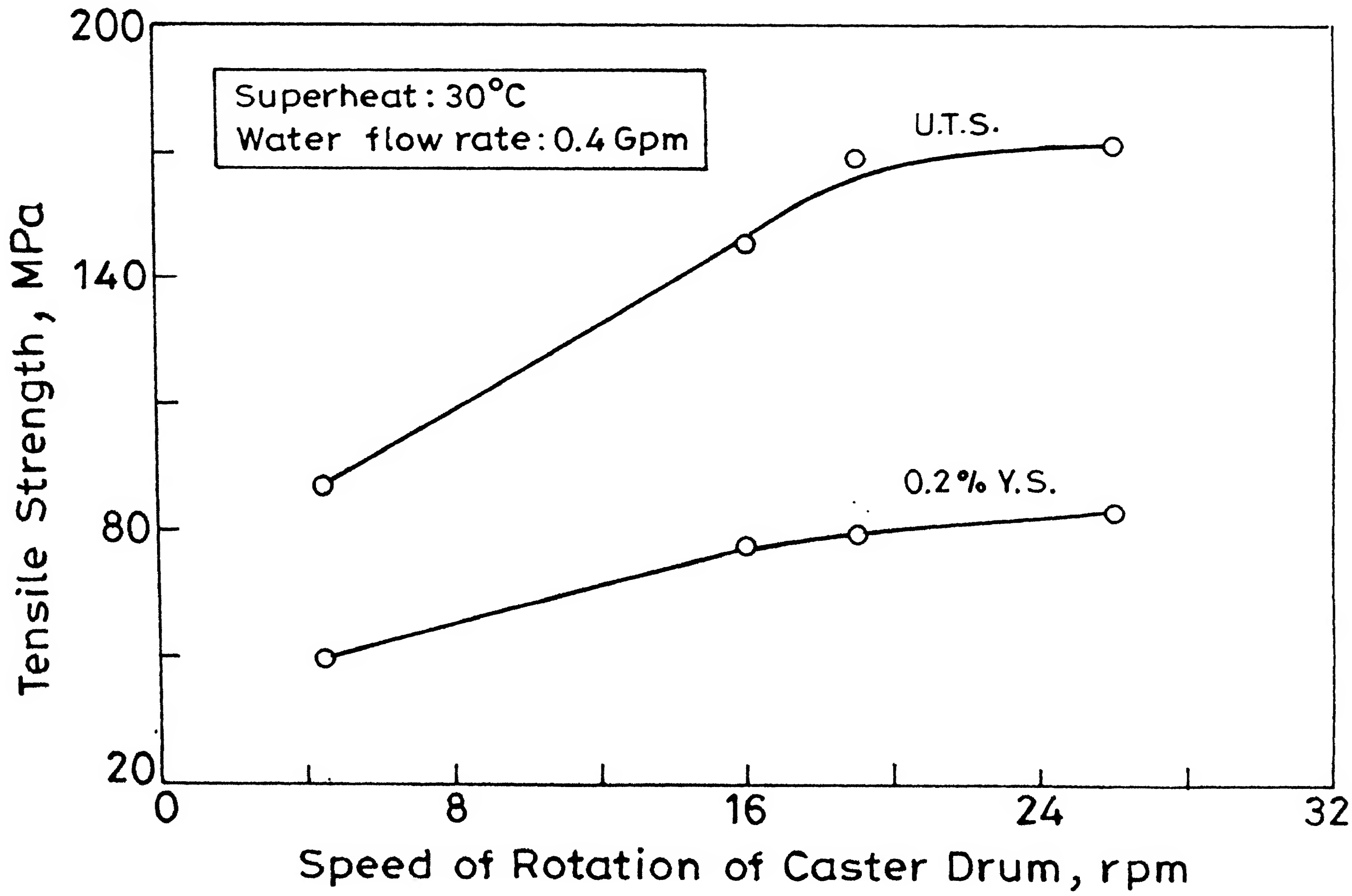


Fig. 4.5 Effect of speed of rotation on As-cast transverse strength

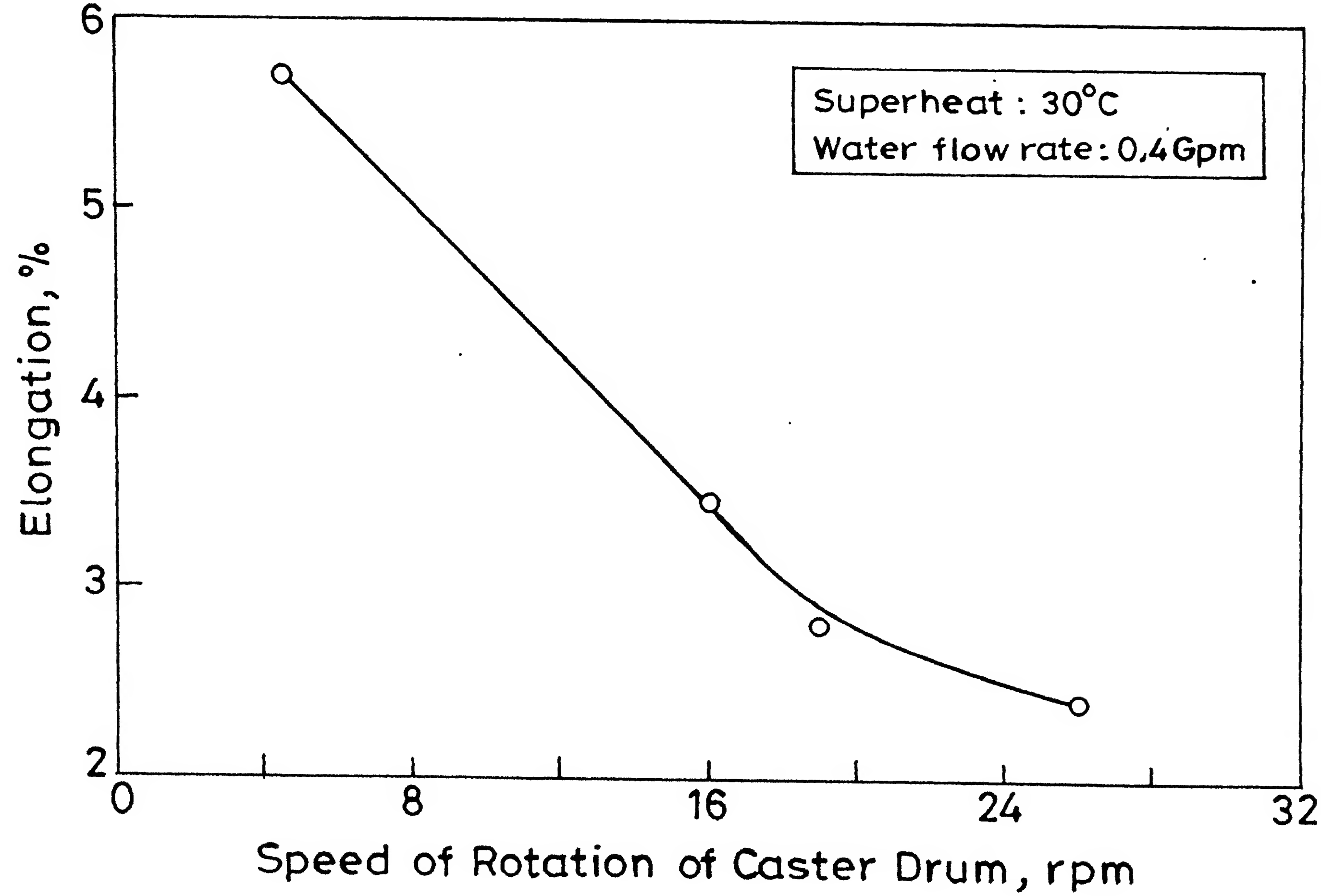


Fig. 4.6 Effect of speed of rotation on As-cast ductility in transverse direction

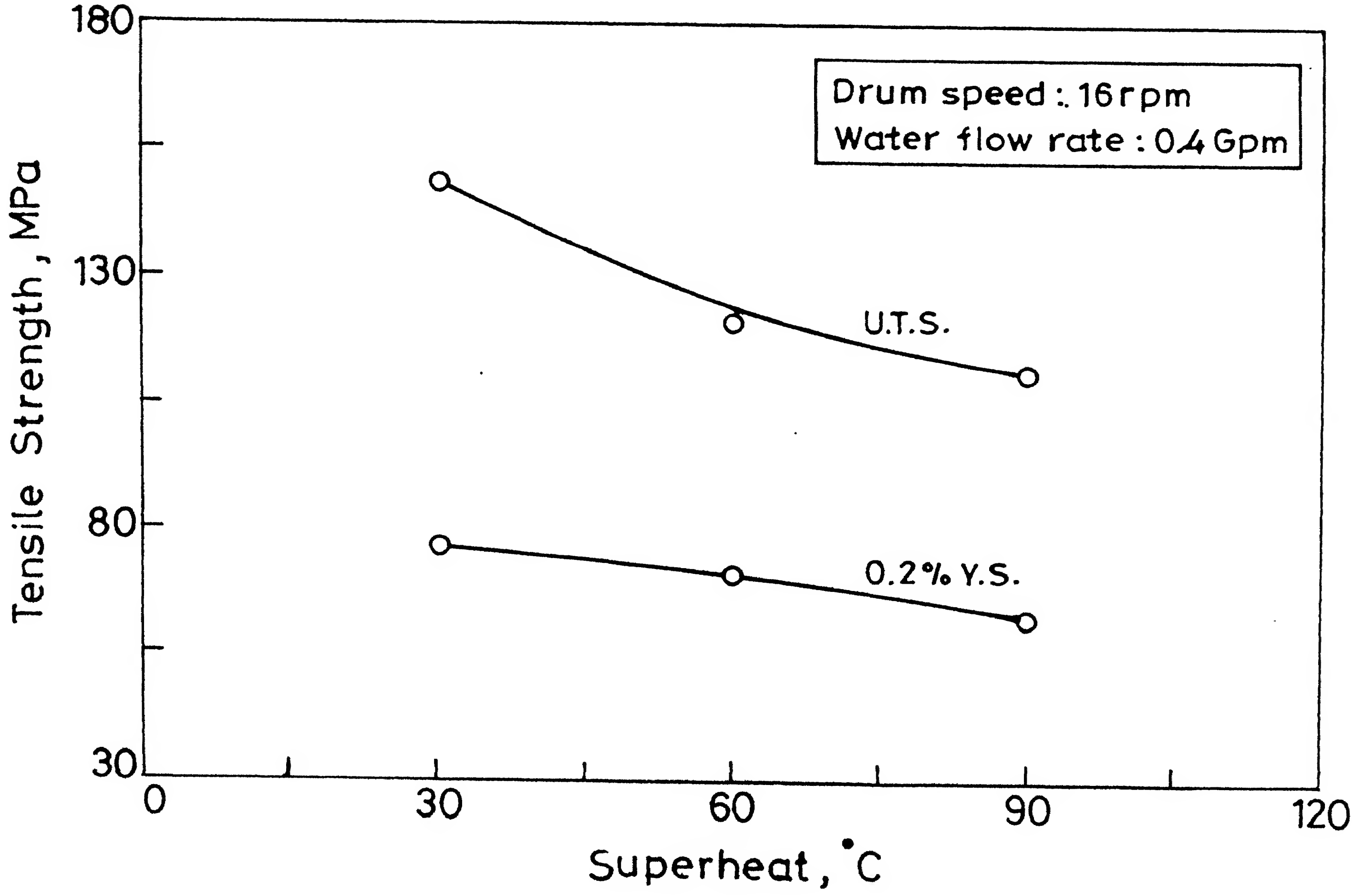


Fig. 4.7 Effect of melt superheat on As-cast transverse strength

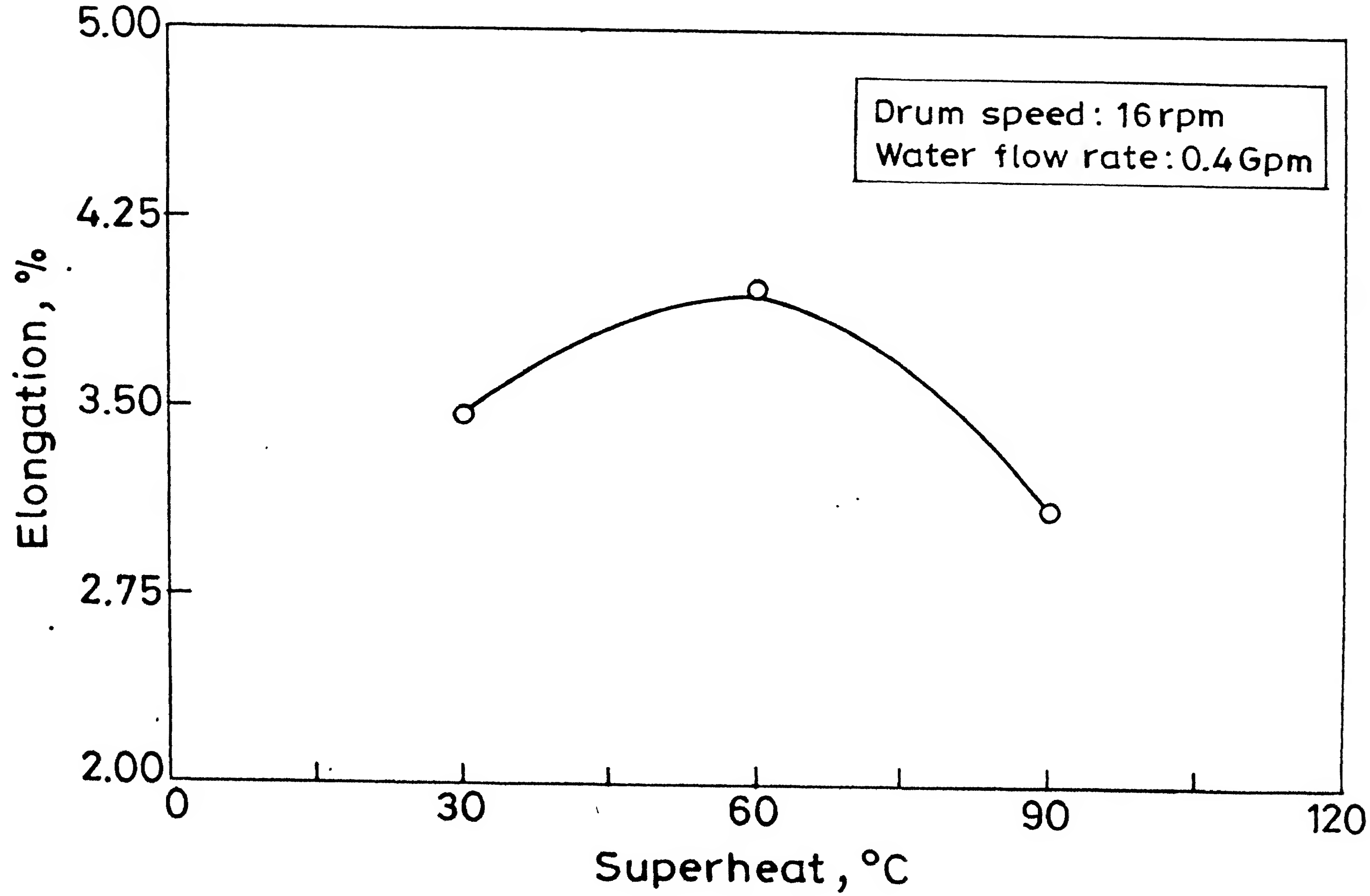


Fig. 4.8 Effect of melt superheat on As-cast ductility in transverse direction

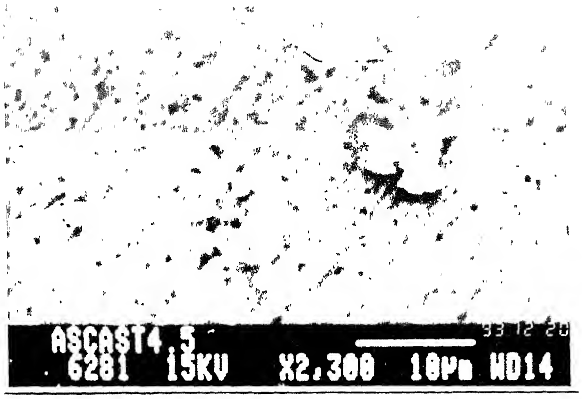
4.1.4.1 Effect of Speed of Rotation of the Caster Drum : The speed of rotation significantly affects the internal porosity. It can be seen in the scanning electron micrographs, in Fig. 4.9, that the porosity of strips produced at 4.5 rpm was smaller in magnitude as compared to that at 26 rpm. This may be attributed to higher rate of solidification at higher rotational speeds which allows lesser time for the entrapped gas to escape.

4.1.4.2 Effect of Melt Superheat : The effect melt superheat on the porosity can be seen in Fig. 4.10. At higher superheat, the porosity was higher in magnitude. This is due to the following reasons : (i) the solubility of gases in molten metal is higher at higher temperature, and (ii) the degree of volume shrinkage also increases with increase in melt superheat.

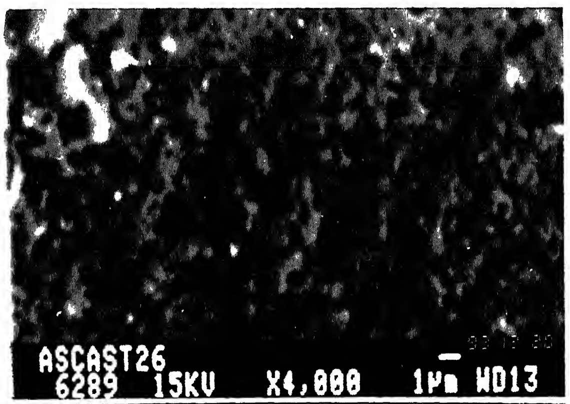
Higher hydrogen content in the melt is particularly undesirable as it may lead to cracking of strips even in the hot rolling process. Therefore, the hydrogen content of the melt should be maintained to less than 8 ppm [11]. In this investigation it has been attempted to do so by treating the molten metal with a chloride flux prior to casting. However due to the non-availability of a hydrogen probe, the final hydrogen content of the metal has remained unknown.

4.1.5 Microhardness

4.1.5.1 Effect of Speed of Rotation of the Caster Drum : The effect of speed of rotation of the caster drum on the microhardness of the as-cast material, for both top-side surface and roll-side surface of the strip is shown in Fig. 4.11. It is seen that there was a

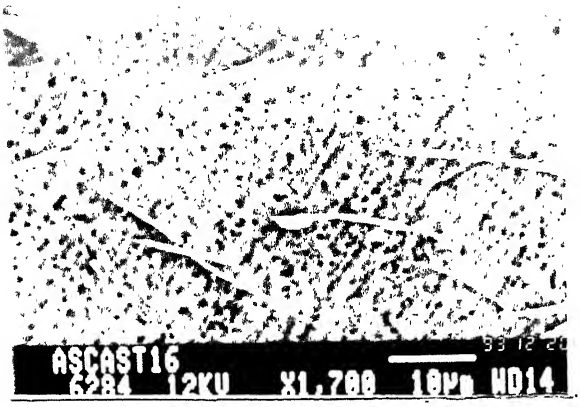


(a) at 4.5 rpm

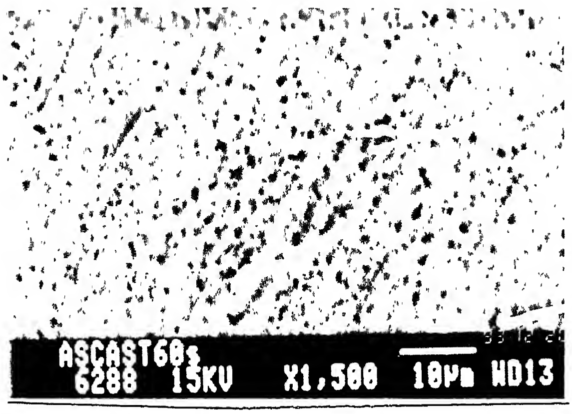


(b) at 26 rpm

Fig. 4.9 Effect of speed of rotation on internal porosity



(a) at 16 rpm, 30°C superheat



(b) at 16 rpm, 60°C superheat

Fig. 4.10 Effect of melt superheat on Internal porosity

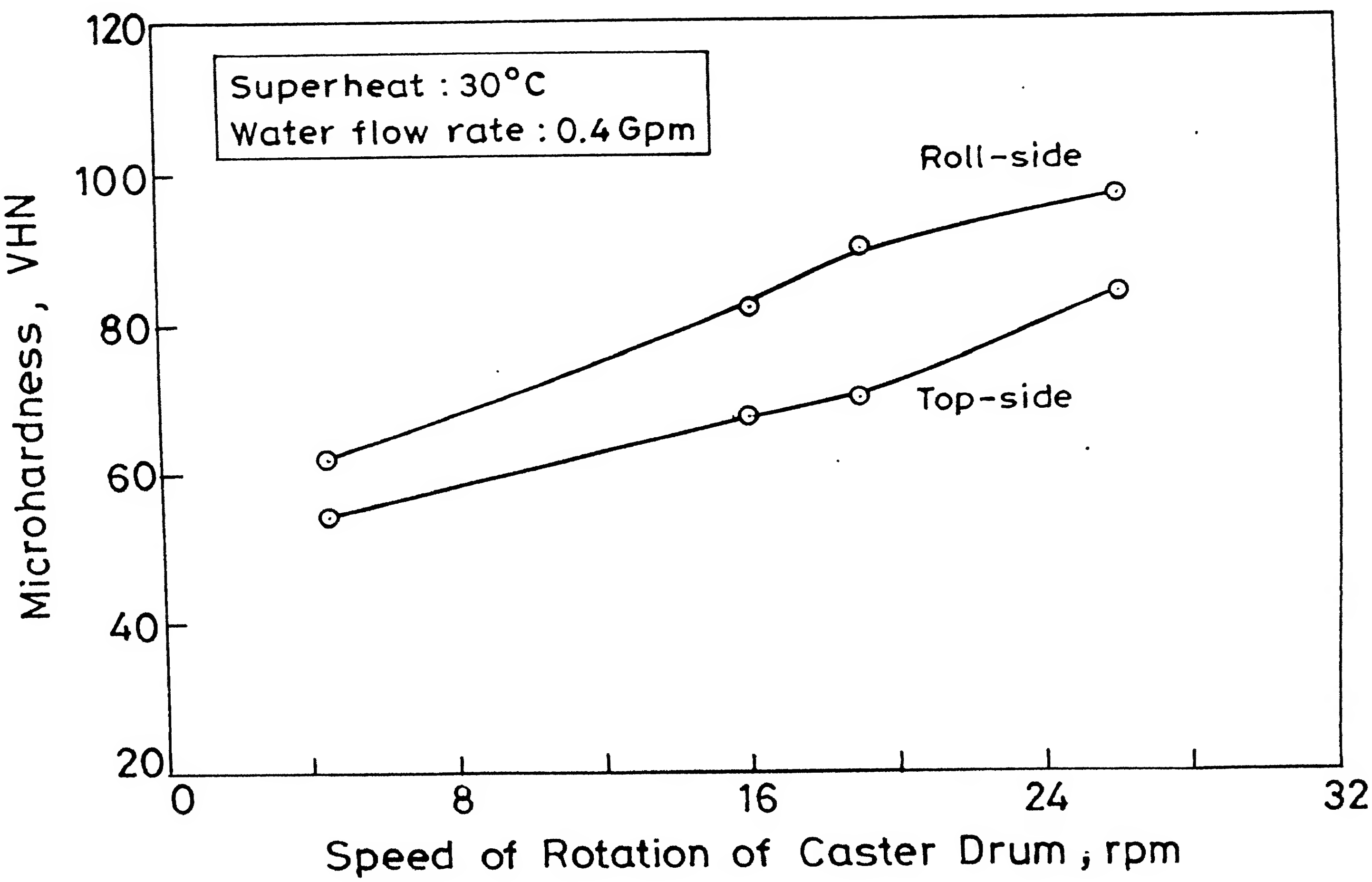


Fig. 4.11 Effect of speed of rotation on microhardness

considerable variance in the microhardness of the strip across the thickness, it was always higher at the roll-side surface of the strip. It is also evident that the microhardness on both sides increased substantially with increasing rotational speed. In figure it is seen that increasing rotational speed from 4.5 to 26 rpm increased the microhardness on the top-side surface of the strip from 54 to 84 VHN while on the roll-side surface it changed from 62.2 to 96.8 VHN.

The reason for increase in hardness at higher rotational speeds is again due to the increase in rate of solidification resulting in finer grains. The variation in hardness across the strip from roll-side surface to top-side surface is related to variance in cooling rate at the two surfaces. The top-side surface is essentially subjected to air cooling while the lower surface, which is in contact with the water cooled drum, experiences quenching effect. Thus, comparatively coarser grains are formed at the top-side surface. These observations are in conformity with those reported in literature for stainless steel [13]. This effect of variation of microhardness across the thickness of the strip must be considered carefully because this results in anisotropic properties.

4.1.5.2 Effect of Melt Superheat : The effect of melt superheat on the microhardness is similar to that of the effect on tensile strength. As shown in Fig. 4.12 for both roll-side and top-side surfaces microhardness decreases with increase in superheat.

4.1.6 Microstructure and Internal Quality of Strips

The effect of speed of rotation and degree of superheat on the

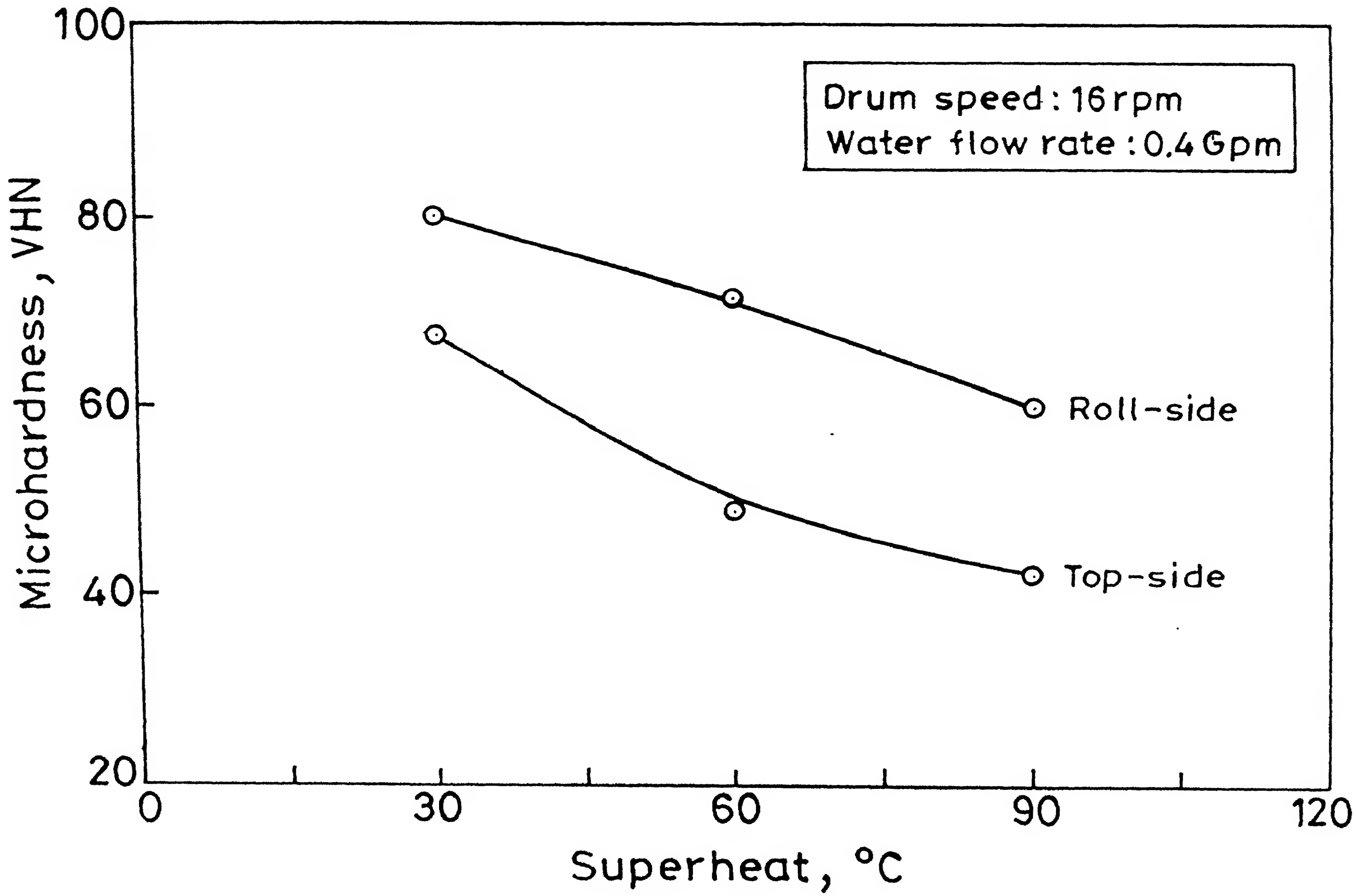


Fig. 4.12 Effect of melt superheat on microhardness

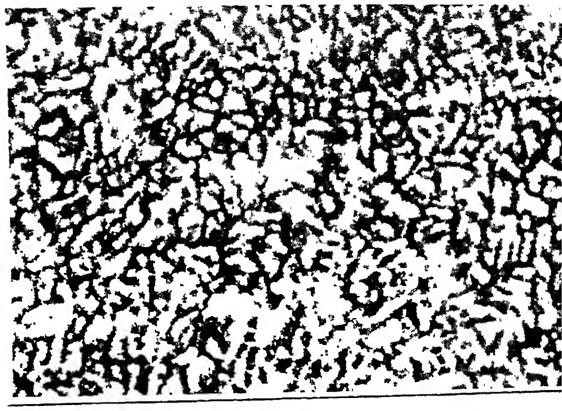
grain size is shown in Fig. 4.13. As discussed previously, the change in grain size is due to the change in rate of solidification. The SEM micrographs reveal that there is a segregation of certain elements other than aluminium such as Fe, Cu, Si, Mn, Zn in the form of long rods (as can be seen in Fig. 4.10). The compositional analyses indicated that iron presence is about 0.8 percent and other elements accounts for 3.2 percent. The presence of iron in the strip material may be partly due to the contamination from the iron rod which is used to stir the melt for degassification before casting, and partly originating from the main raw material with other elements mentioned above. This raw material is procured from local market. The micrographs also revealed the presence of some non-metallic inclusions. These inclusions may either come due to the erosion of refractory material of the tundish or due to the segregation of other non-metallic phases. These inclusions will adversely affect the mechanical properties of the strips. During further processing of strips, the material may rupture due to the inclusion nucleated fracture. As these inclusions cannot be removed during casting process, it is of paramount importance that the melt used for casting is clean and adequately deoxidised.

4.2 COLD ROLLED AND ANNEALED STRIPS

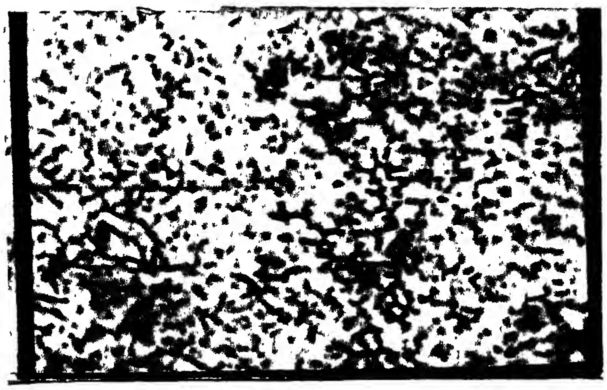
4.2.1 Strength and Ductility

The strength and ductility values obtained in as-rolled conditions (cold rolled but not annealed) show similar trend as that for a conventionally cold rolled product in which the strength increases and ductility decreases with increase in deformation. The samples taken out from the strips produced at higher melt superheats

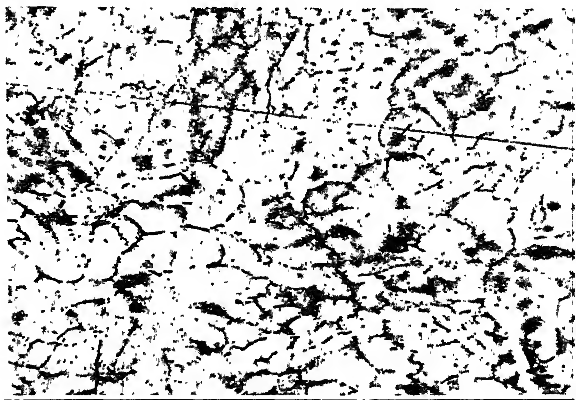
(a) at 4.5 rpm, 30°C superheat



(b) at 19 rpm, 30°C superheat



(c) at 16 rpm, 30°C superheat



(d) at 16 rpm, 60°C superheat

Fig. 4.13 Optical micrographs obtained for As-cast material

(above 90°C) are prone to surface cracks during cold rolling. However the samples taken out from the strips produced at various rotational speeds from melt with 30°C superheat the surface finish is excellent and the samples are free from any surface defects. These cold rolled samples could be annealed at recrystallization temperature of aluminium for various time durations to get the improved strength and ductility.

The strength and ductility of samples produced under various operating conditions, cold rolled to 20 and 30 percent deformation and then annealed for 3 hours are tabulated in Table 4.1. These values are in reasonable agreement with that of commercial strips (discussed in section 4.5).

4.2.2 Microstructure and Internal Quality

Figure 4.14 shows the effect of cold rolling (30%) and annealing on microstructure for the strip samples produced at 16 rpm and 30°C superheat. These micrographs have been obtained to examine the effect on segregation, inclusions and grain size. The segregates which are long in as-cast material are broken and finely distributed in the matrix as can be observed in Figs 4.14 (a) and 4.10 (a). It can be noticed that some inclusions of even spherical shape are present in the matrix. The grain size is larger than that of as-cast material as can be observed in Figs 4.14(b) and 4.13(c).

4.3 HOT ROLLED STRIPS

4.3.1 Strength

Figures 4.15 and 4.16 show the tensile strength (U.T.S) as a function of percentage deformation in longitudinal and transverse

Table 4.1 Strength and ductility of Annealed strips

RPM-	Cold rolling, %	Strength (U.T.S), Mpa	Elongation, %
4.5	20	70.6	8.2
16	20	92.8	5.65
26	20	116.1	4.56
4.5	30	80.6	6.7
16	30	100.2	5.6
26	30	120.3	3.1

(a) SEM micrograph

(b) Optical micrograph (50x)

Fig. 4.14 Micrographs obtained for annealed samples after 30% cold rolling (16 rpm, 30^{0}C superheat)

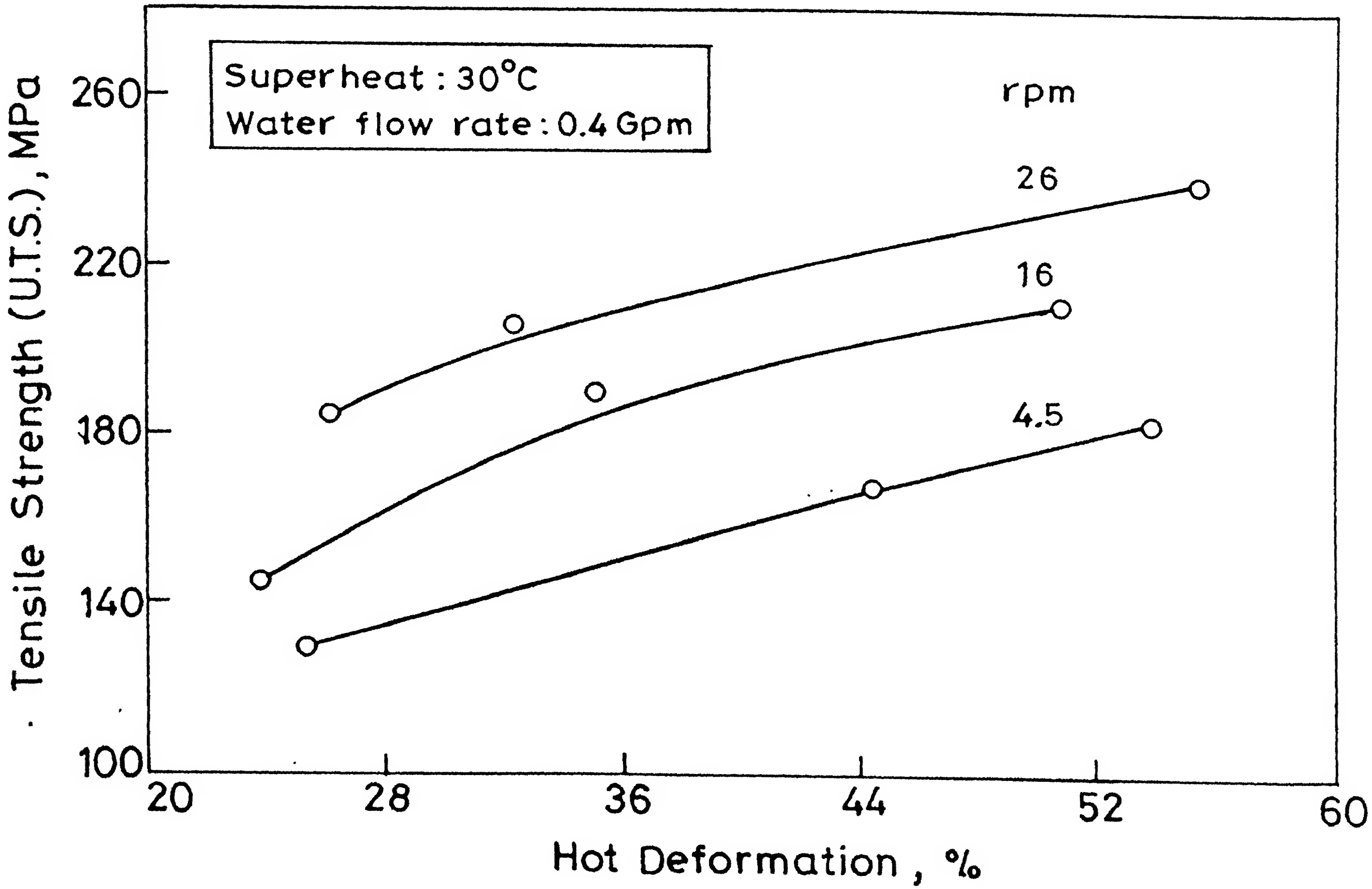


Fig. 4.15 Effect of hot rolling on longitudinal strength

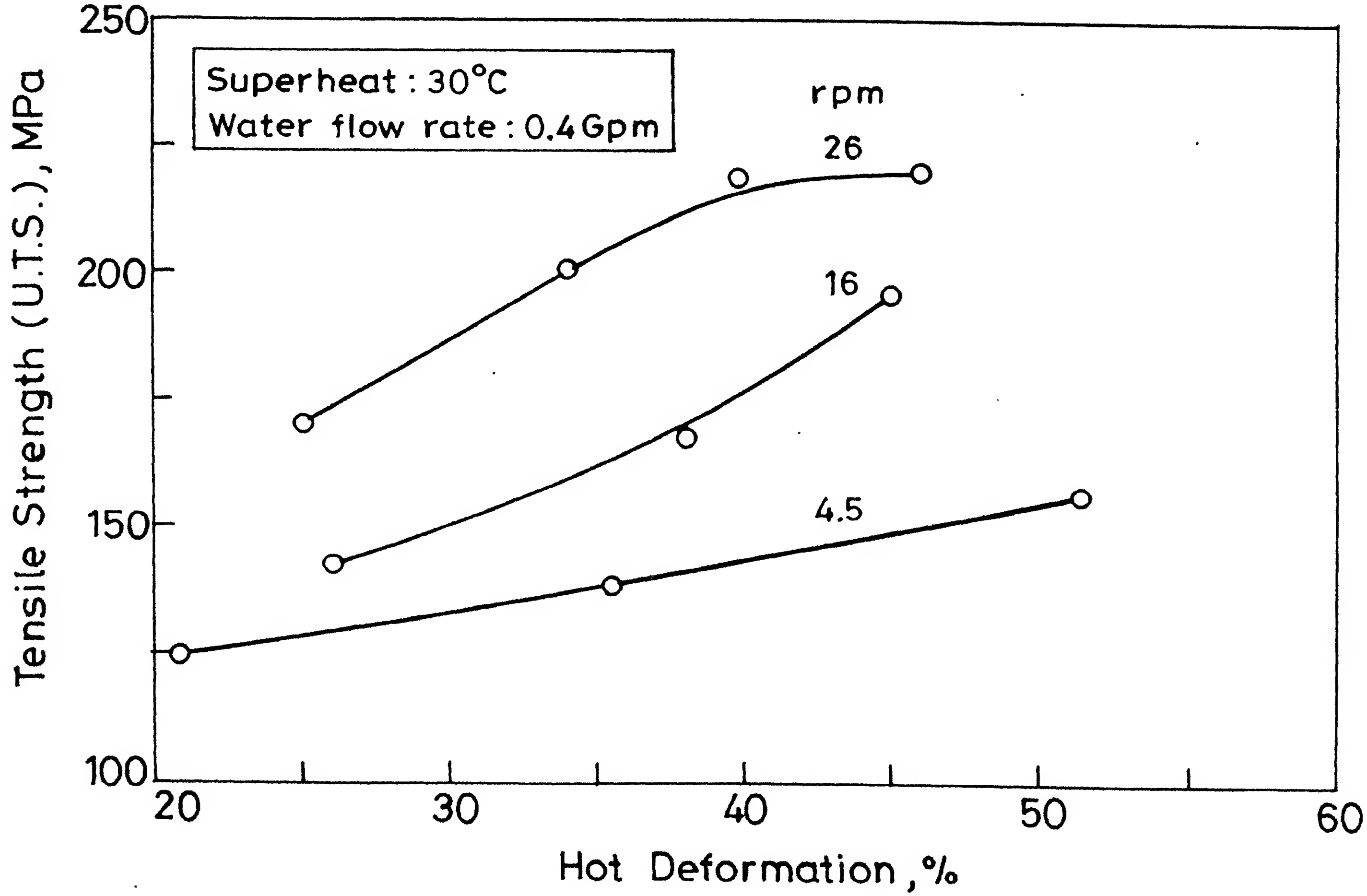


Fig. 4.16 Effect of hot rolling on transverse strength

directions, respectively for strips cast at various caster drum rotational speeds and then hot rolled to varying degrees of deformation. It is to be noted that the ultimate tensile strength increased for three casting speeds, namely 4.5, 16 and 26 rpm. For a given percentage of deformation the strength was high for strips cast at higher rotational speeds.

Figure 4.17 shows the variation of tensile strength with degree of deformation in longitudinal direction for strips produced from melt at 30 and 60 ^{o}C superheats, respectively. The strength increased with increasing degree of deformation in both the cases. For the strips produced from melt with 30^{o}C superheat the strength was high as was observed in as-cast strips.

The increase in strength with increase in deformation is likely to be due to the following reasons : (i) formation of smaller grains at higher deformations, and (ii) closure of pores.

4.3.2 Ductility

Figure 4.18 shows the effect of deformation on ductility of the strips produced at three different rotational speeds and a melt superheat of 30 ^{o}C. It is seen that the ductility in longitudinal direction is increasing with increased degree of deformation. The reason for increase in ductility is due to the increased annihilation of pores with increased deformation. The effect of superheat on ductility is shown in Fig. 4.19. It is observed that the elongation increases with increased deformation for the strips produced at 30^{o}C superheat while it is decreasing for the strips produced from melts with 60^{o}C superheat. As mentioned earlier

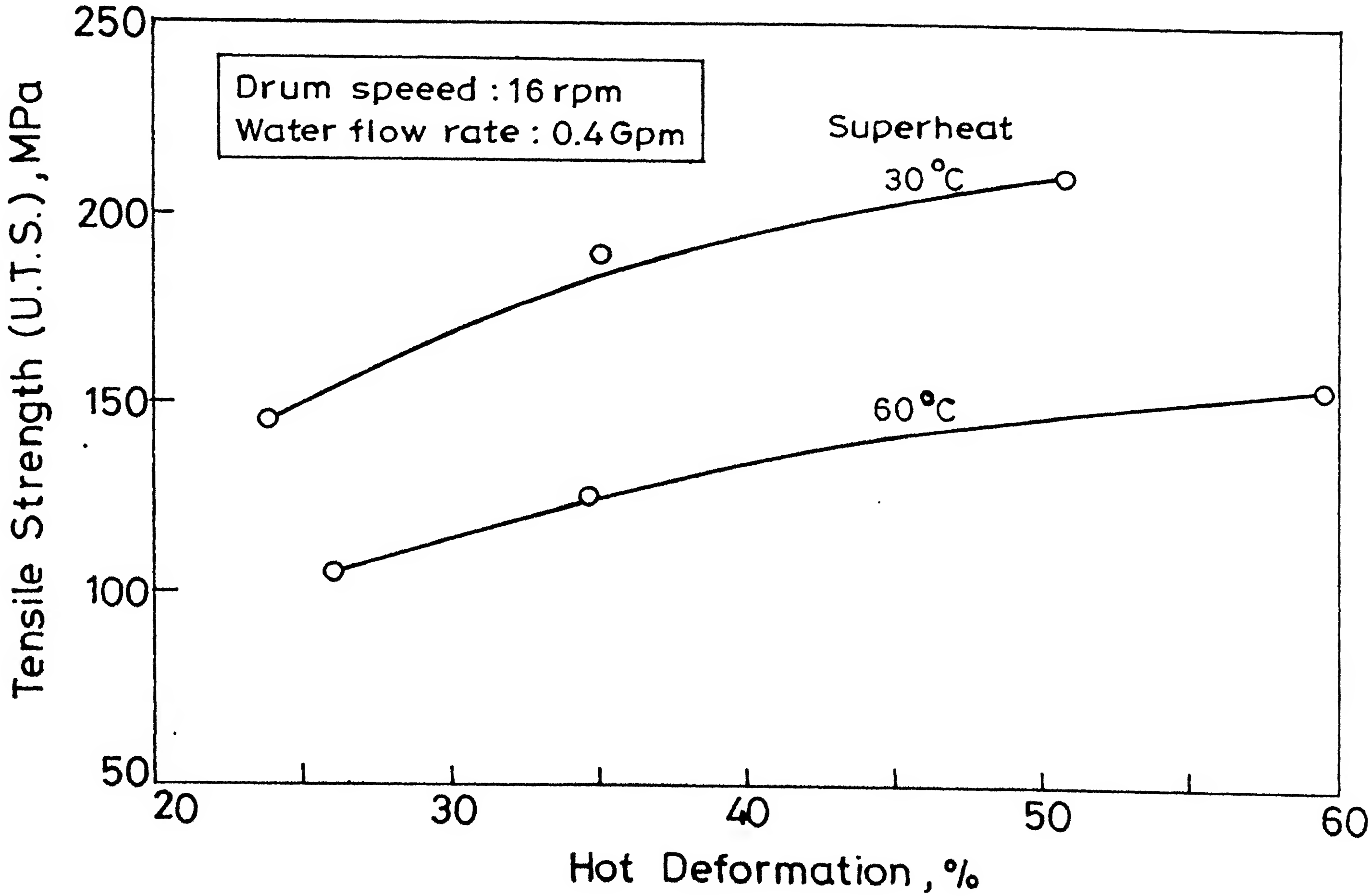


Fig. 4.17 Effect of hot rolling on longitudinal strength for the strips of different degrees of superheat

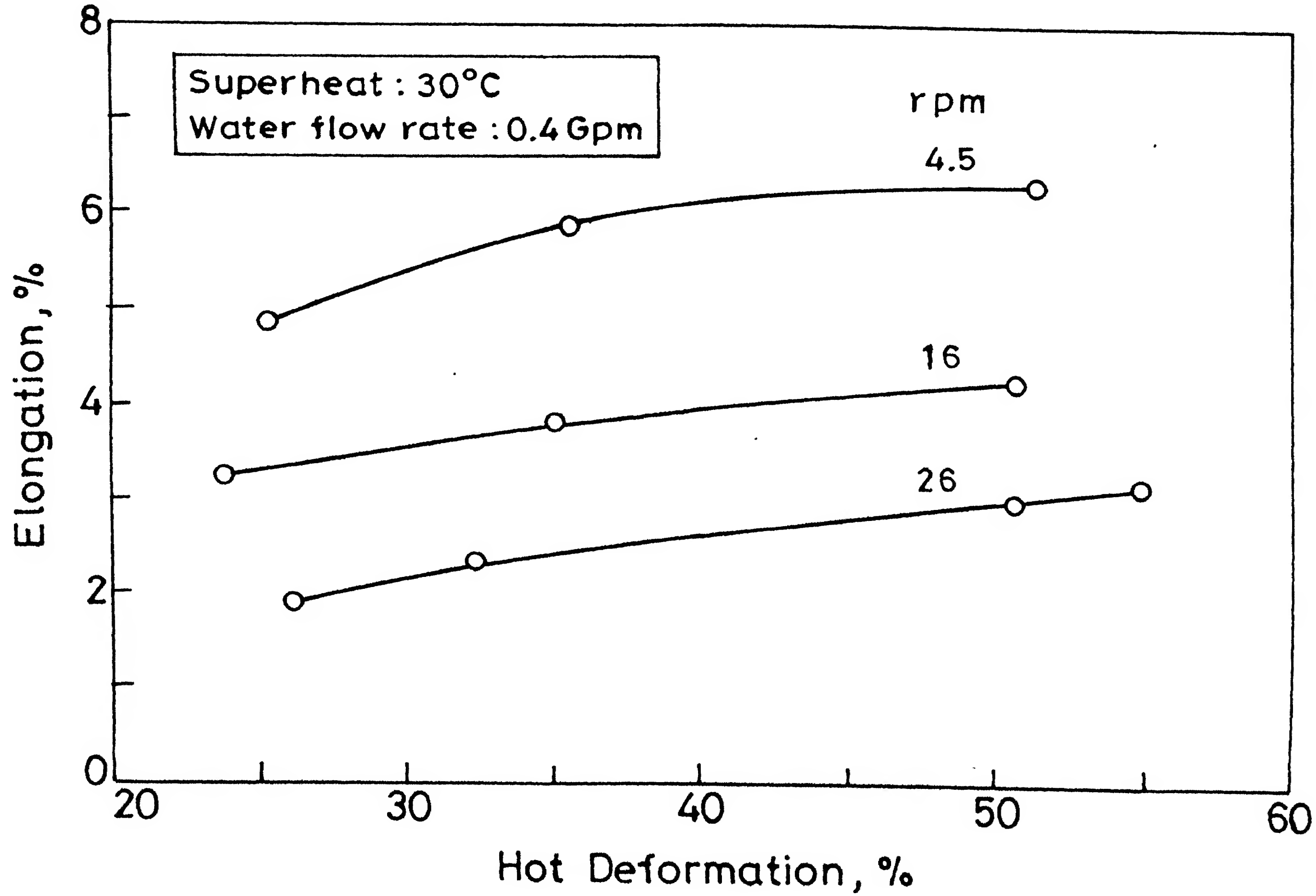


Fig. 4.18 Effect of hot rolling on ductility in longitudinal direction

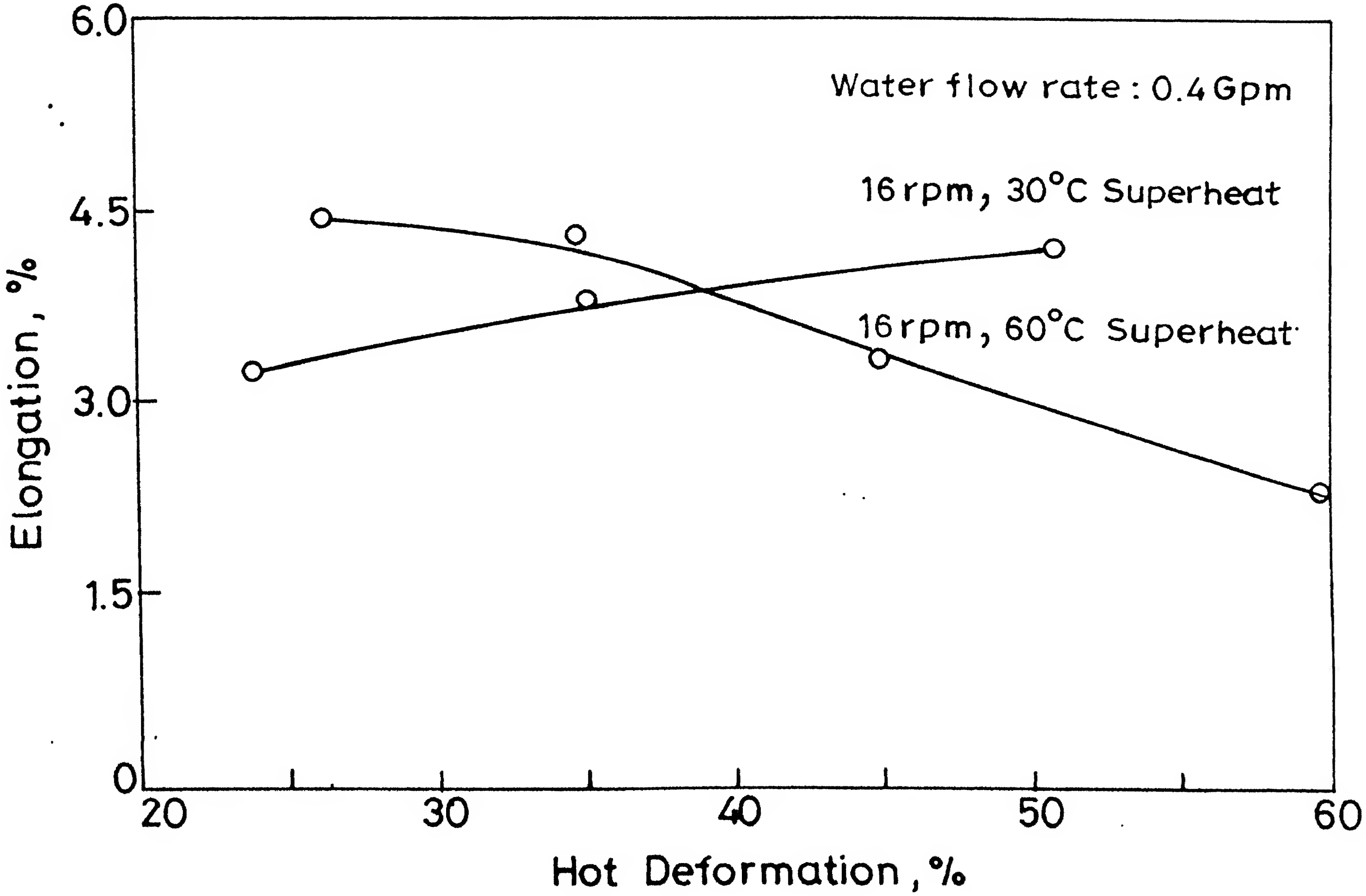


Fig. 4.19 Effect of hot rolling on ductility in longitudinal direction for the strips of different degrees of superheat

porosity of strips increases with increasing melt superheat. Thus, the strips formed from melts with 60°C superheat having both the higher porosity as well as larger pores as compared with melt superheat of 30°C. While in the latter strips the pores annihilation on higher degree of hot rolling, in the case of former, internal cracking was observed. The extent of cracking increased with increasing degree of deformation resulting in reduced ductility (details of microstructures are given in the subsection 4.3.4). For the strips produced from melts with 90°C superheat surface cracks were observed on hot rolling. Therefore, higher superheats are not desirable from the point of view of rolling.

4.3.3 Microhardness

The effect of both the rotational speed and the degree of superheat on microhardness with deformation at is shown in Fig. 4.20. The variance in hardness across the strip thickness is not considerable in the hot rolled samples when compared to as-cast samples. It can be observed from the figure that the microhardness increases with increasing deformation and that for a given value of deformation it is higher for the strips produced at higher rotational speeds and smaller degrees of superheat. It is attributed to the smaller grain size.

4.3.4 Microstructure and Internal Quality

The effect of hot deformation on microstructure is shown in Figs 4.21 and 4.22. This effect for the samples produced at 16 rpm, 30°C superheat is given in Fig. 4.21 while Fig. 4.22 is for the samples that are produced at 16 rpm and 60°C superheat. The

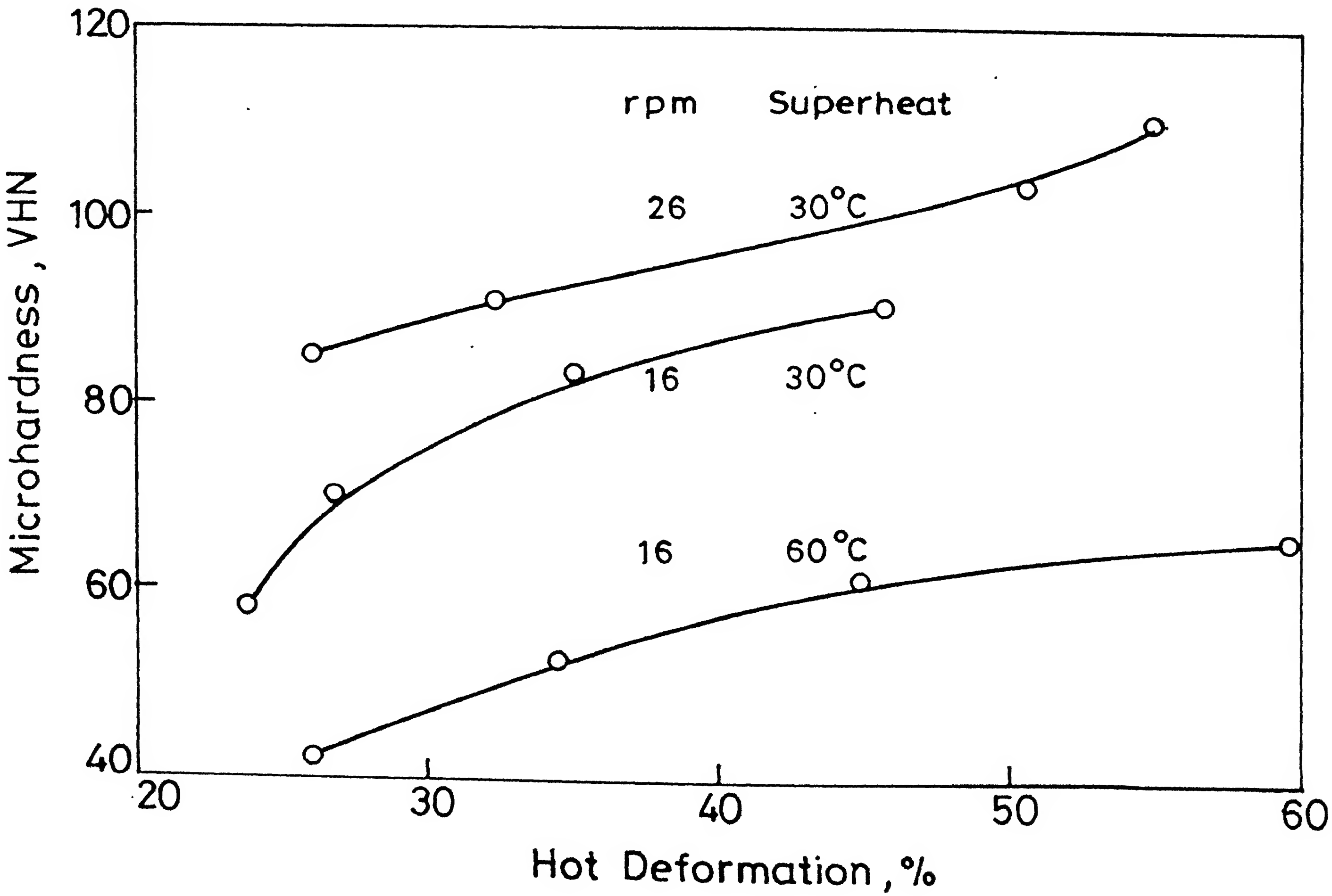
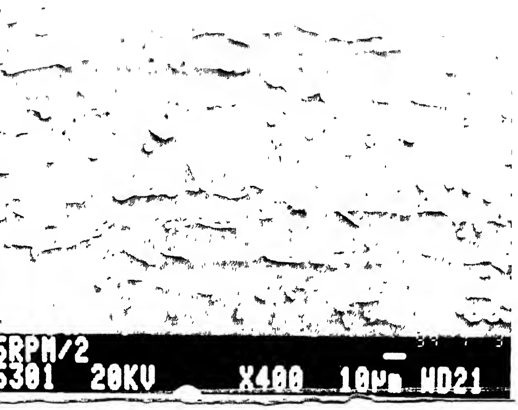


Fig. 4.20 Effect of hot rolling on microhardness



(a) SEM micrograph after

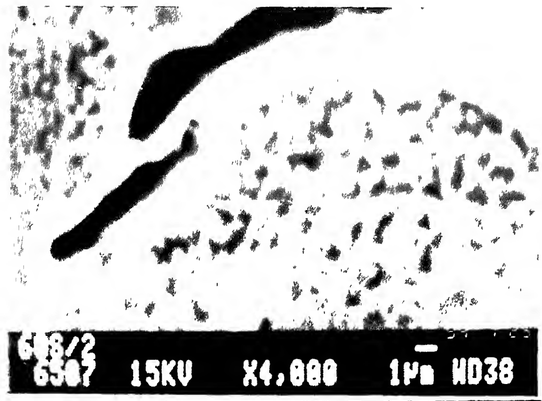
25% deformation

(b) Optical micrograph after

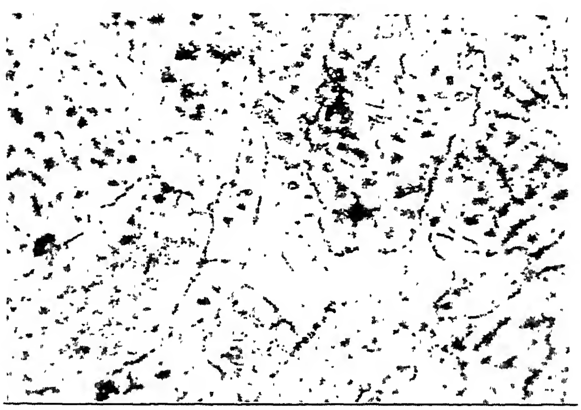
35% deformation (50x)

(c) Optical micrograph after 45% deformation (50x)

Fig. 4.21 Micrographs obtained for hot rolled samples (16 rpm, $30^{\circ}C$ superheat)



(a) SEM micrograph after 30% deformation



(b) Optical micrograph after 45% deformation (50x)

Fig. 4.22 Micrographs obtained for hot rolled samples of $60^{o}C$ superheat (16 rpm)

segregates in this case (hot rolling) also are broken and finely distributed. The grains are elongated in the direction of rolling (in 30°C) and the degree of elongation is increasing with increase in deformation as can be observed from Figs 4.21(b) and 4.21(c). The effect of hot rolling on the samples that are produced at 60°C superheat is very different from that produced at 30°C superheat. In the latter case there is no internal cracking during deformation, but in the case of the former internal cracks of larger magnitude are observed, Fig. 4.22(a). This is perhaps due to the higher hydrogen entrapment during casting because of higher superheat. The grain size after 45% deformation is also different from that of 30°C superheat in which the grains are elongated in the direction of rolling as can be noticed in Figs 4.21(c) and 4.22(b).

4.4 MECHANICAL PROPERTIES OF ALUMINIUM FLAT PRODUCTS AS REPORTED IN LITERATURE

The mechanical properties of aluminium are very much dependent upon the purity of the material. Mechanical properties vary appreciably even as the purity changes from 99.5 to 99.9 percent. Some typical mechanical properties of aluminium ranging in purity from 99.5 to 99.99 percent are shown in Table 4.2 in which strength is increasing while ductility is decreasing with increase in purity. The most common elements that are present in commercial aluminium [14] are Si, Cu, Mn, Mg, Zn and Fe. These elements are either impurities or alloying additions. Each element has an effect on microstructure. In addition, each step in the fabricating process and each thermal treatment may alter the structure. Thus, the structure of aluminium product represents the composite effects of composition and of the various mechanical and thermal treatments

Table 4.2 Mechanical properties of pure Aluminium [14]

Purity, %	Tensile strength, psi	Brinell hardness	Elongation, %
99.99	6500	12-16	50
99.80	9000	19	45
99.70	9500	19	43
99.50	10000	18-25	42

involved in its manufacture.

The commercial products such as sheet, strip and foil are designated as commercial wrought alloys. These alloys are classified into heat-treatable and non heat-treatable depending upon their heat-treatable properties. These properties are more sensitive to chemical composition of alloying elements. The mechanical properties will change considerably even for a small change in composition as can be observed from Tables 4.3 and 4.4. From Table 4.3 it can be noted that the strength and ductility also vary with strip thickness. Cold deformation increases both shear strength as well as tensile strength, while it deceases ductility. The recrystallization temperature for cold deformed material depends upon the degree of deformation and alloying elements. For example increase in cold deformation the recrystallization temperature decreases.

4.5 COMPARISON OF PROPERTIES OF CAST STRIPS WITH COMMERCIAL STRIPS

The surface quality of strip quality material is poor in comparison with commercial strips. The roll-side surface is reasonably good and the top-side surface is rough. The degree of roughness is increasing with increase in strip thickness.

The strength and ductility of commercial, as-cast, hot rolled and annealed strips along with their gauge thickness have been measured and tabulated in Table 4.5. The strips produced at 4.5, 16 and 26 rpm are having same melt superheat and cooling rate. The values listed, for 30 percent hot rolled strips are obtained by interpolation from Figs 4.15 and 4.18. It is to be noticed that strength as well as the ductility of commercials strips vary with

Table 4.3 Chemical composition of Aluminium alloys (wt%) [15]

Alloy Designation	Si	Fe	Cu	Mn	Mg	Zn
A 5052	0.45	0.35	0.10	0.10	2.2-2.8	0.10
A 7072	0.70	0.35	0.10	0.10	0.1	0.8-1.3
A 7075	0.40	0.50	1.2-2.0	0.30	2.1-2.9	5.1-6.1
A 7078	0.40	0.50	1.6-2.4	0.30	2.4-3.1	6.3-7.3
A 7179	0.30	0.40	0.4-0.8	0.1-.3	2.9-3.7	3.8-4.8

Table 4.4 Mechanical properties of Aluminium alloys [15]

Alloy	Strip thickness, in	Tensile Strength, ksi	Elongation, %
A 5052	0.006-0.007	15.0	12
	0.051-0.249	15.0	16
	0.250-3.00	15.0	22
A 7075	0.08-0.011	68.0	5
	0.04-0.059	70.0	7
	0.063-0.187	73.0	8
A 7178	0.015-0.499	40.0	10

Table 4.5 Comparison of properties with commercial strips

RPM	Condition	Thickness mm	Strength (U.T.S), Mpa	Elongation %
	Commercial	2.8	62	10.3
	Commercial	2.0	76	7.9
	Commercial	1.4	92	6.18
	Commercial	0.8	110.8	3.3
4.5	As-cast	2.77	66.87	5.6
16	As-cast	2.27	126.0	3.47
26	As-cast	1.3	137.0	2.5
4.5	Annealed	2.0	80.6	6.7
16	Annealed	1.45	100.2	5.6
26	Annealed	0.91	120.3	3.1
4.5	30 % hot rolling	2.0	132	5.4
16	30 % hot rolling	1.45	175	3.5
26	30 % hot rolling	0.91	194	2.2

strip thickness. Using these tabulated values, graphs are drawn for strength and ductility as a function of thickness for the as-cast, hot rolled, annealed and commercial strips, and are presented in Figs. 4.23 and 4.24.

It can be seen in Fig. 4.23 that the as-cast strength is more than that of commercial strips while for annealed strips the strength is comparable or even better than that of commercial strips. The strength after 30% hot deformation is higher than the strength of the as-cast strips.

Figure 4.24 shows that the ductility of the as-cast material is about 50 percent that of the commercial strips of the same thickness. The ductility in case of hot rolling, even though it is increasing from as-cast value, is far away from commercial strips. However after cold rolling to 30 percent deformation and then annealing at recrystallization temperature for 3 hours, the ductility obtained in the strip cast material is close to the commercial strips (about 90%). The reason for less ductility is perhaps due to the presence of some non-metallic inclusions which are originating from the erosion of tundish refractory material and segregates in the rod form. These segregates are basically iron aluminides with other elements such as Cu, Zn, Mg and Si in small percentage. The presence of iron may be partly due to the contamination of iron rod which is used to stir the melt during degassification, partly originating from raw material. The composition of this material falls in the range of 7xxx alloys. Due to the sensitiveness of the compositional varience it is difficult to designate the particular type of alloy. Entrapment of hydrogen

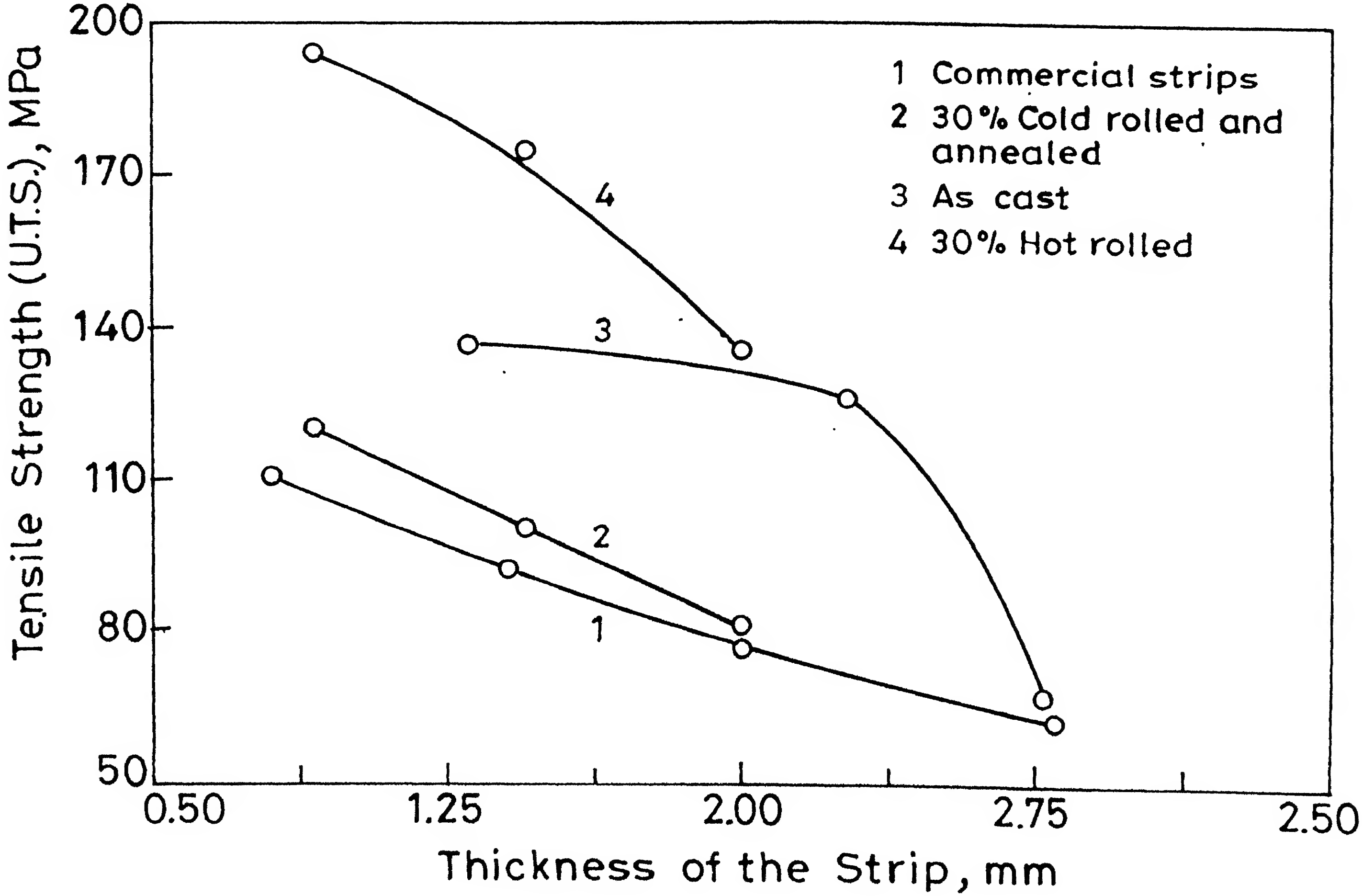


Fig. 4.23 Comparison of strength of cast strips with commercial strips

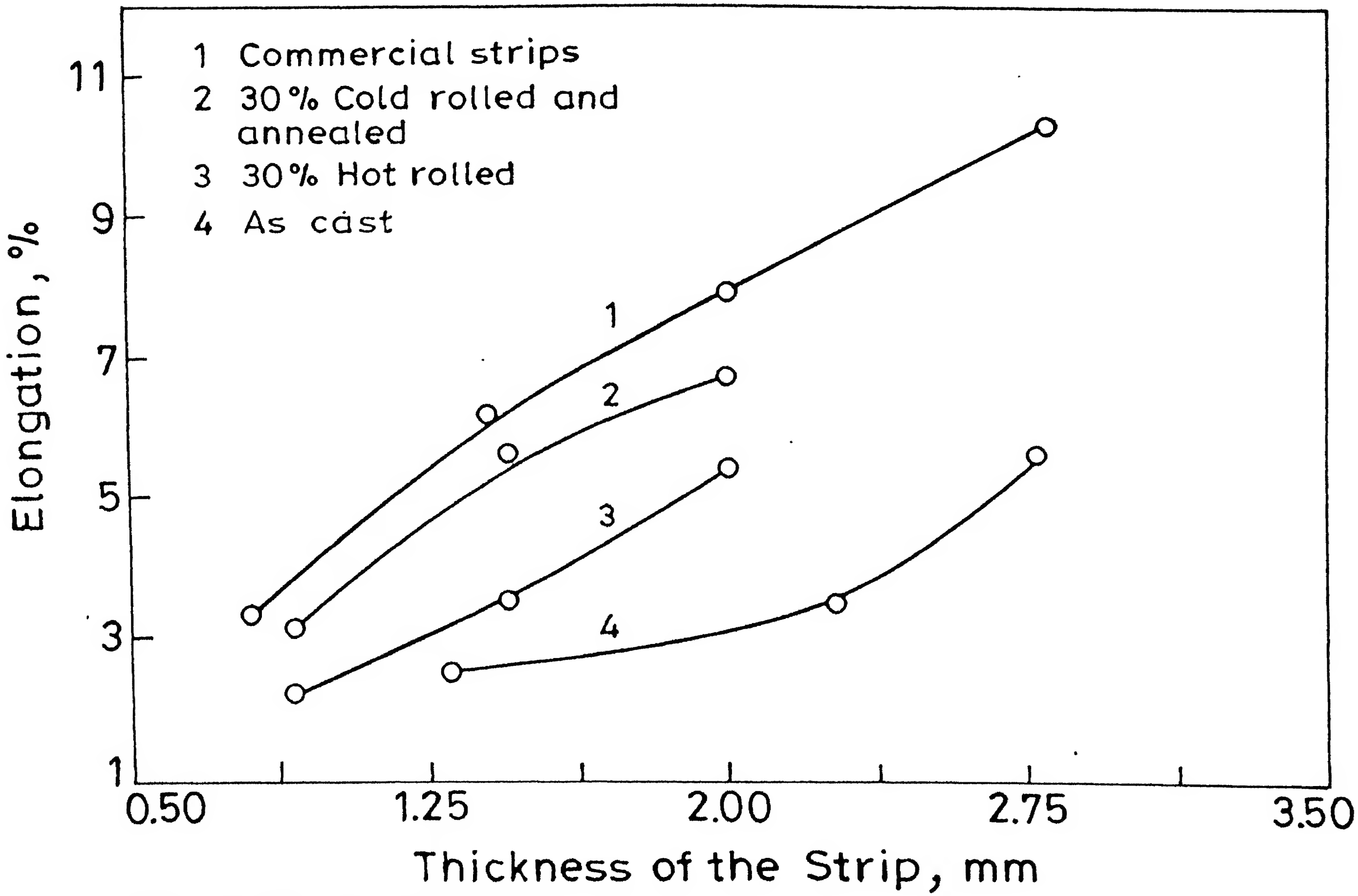


Fig. 4.24 Comparison of ductility of cast strips with commercial strips

also decreases the ductility, by increasing the internal poro

The top-side surface quality can be improved by introdu(press roll over the drum. Though the press roll is present i original design of the caster, in the present work it has not installed. The non-metallic inclusions in the strip cast ma1 can be minimized by using better quality tundish and the segre can be avoided by chosing high purity raw material. The hydı entrapment can be minimized by properly degassing the molten m with appropriate flux of good quality. Though the strip (products are inferior to commercial products, particularly in te of ductility, it can be improved as suggested above.

also decreases the ductility, by increasing the internal porosity.

The top-side surface quality can be improved by introducing a press roll over the drum. Though the press roll is present in the original design of the caster, in the present work it has not been installed. The non-metallic inclusions in the strip cast material can be minimized by using better quality tundish and the segregates can be avoided by chosing high purity raw material. The hydrogen entrapment can be minimized by properly degassing the molten metal with appropriate flux of good quality. Though the strip cast products are inferior to commercial products, particularly in terms of ductility, it can be improved as suggested above.

CHAPTER 5

CONCLUSIONS

The present investigation primarily involved in the evaluation of mechanical properties and microstructure of aluminium strips produced using a laboratory scale single roll continuous strip caster, designed and fabricated by Mehrotra and coworkers. The mechanical properties such as strength, ductility and microhardness were examined for the strips produced at various operating parameters. The effect of operating parameters such as speed of rotation of the caster drum, melt superheat on the properties of as-cast, cold rolled and annealed, hot rolled (at 500°C) strips were examined. The effect of these operating parameters on the surface quality in as-cast strips were also examined. Microstructural investigation has been done using SEM and optical microscopy.

More than 90 experiments have been conducted. From the analysis of the experimental data the following conclusions have been drawn :

(i) The roll-side surface of the strip cast material is smooth, while the top-side surface is rough. The degree of roughness increases with increase in strip thickness. Transverse cracks are also dominant at higher strip thickness.

(ii) Strength of as-cast material is high where as the ductility is low in comparison with commercial strips. However, the ductility is improved by annealing after 30% cold working.

(iii) Internal porosity in the strip cast products increased with the increase in rotational speed of the caster drum and melt

superheat.

(iv) Grain size is small at higher rotational speeds of the caster drum and at lower melt superheats.

(v) There is a considerable varience in microhardness of as-cast strips from roll-side surface to top-side surface. However, there is no considerable varience in the microhardness of the hot rolled strips.

(vi) There is increase in strength and ductility of strip cast materials with increase in degree of hot deformation. However, the ductility is still inferior to commercial strips. The strips produced at higher melt superheats are subjected to internal cracking even in hot rolling process.

(vii) Low ductility of strip cast products in comparison with commercial strips is due to the presence of non-metallic inclusions and segregates.

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